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NUMERIČKA SIMULACIJA INERTIRANJA TANKOVA TERETA

NUMERICAL SIMULATION OF CARGO TANKS INERTING

SAŽETAK

U radu je prikazana problematika inertiranja tankova na brodovima za prijevoz tekućeg tereta. Opisan je sustav za proizvodnju inertnoga plina te su navedeni zahtjevi koje takav sustav mora ispunjavati. Istaknuti su čimbenici koji utječu na kvalitetu inertiranja tankova tereta te karakteristike različitih pristupa pri upuhivanju inertnoga plina. Nadalje, je prikazan matematički model korišten u numeričkoj simulaciji inertiranja te njegova primjena na primjeru tankera za prijevoz tekućeg tereta. Numerička simulacija inertiranja provedena je za slučaj prvog inertiranja tanka nakon primopredaje broda ili inertiranja nakon dokovanja broda. Obradeno je više slučajeva s različitim smjerovima upuhivanja inertnoga plina u tank tereta sa svrhom određivanja optimalnog smjera. Provedeno je i istraživanje utjecaja brzine upuhivanja inertnoga plina na brzinu promjene koncentracije pojedinih plinova. U zaključku je dan osvrt na dobivene rezultate uz smjernice za poboljšanje predstavljenoga simulacijskog modela.

Ključne riječi: inertiranje, tankovi tereta, numerička simulacija, metoda konačnih volumena

SUMMARY

The topic of cargo tanks inerting on board liquid cargo carriers is presented in this paper. The inert gas production system and requirements which such a system has to fulfil are described. Factors that influence the quality of cargo tank inerting as well as different approaches to cargo tanks inerting are pointed out. The mathematical model used in the numerical simulation of cargo tanks inerting and its application on the example of a liquid cargo carrier is described in the paper. The numerical simulation of inerting is performed for a case of the first cargo tank inerting after the ship delivery or after docking. Several examples of different inert gas injection directions were analyzed with an intention to find out an optimal inert gas injection direction. Furthermore, the influence of the inert gas injection velocity on the gas concentration change rate inside the cargo tank is investigated. An overview of the obtained results and guidelines for the improvement of the presented simulation model are given in the conclusion chapter.

Key words: inerting, cargo tanks, numerical simulation, finite volume method

1. UVOD

Tijekom eksploatacije brodova za prijevoz tekućeg tereta postoji povećana opasnost od požara i eksplozije zbog specifičnih karakteristika tereta koji prevoze. Takvi su brodovi opremljeni sustavima inertnoga plina koji omogućuju održavanje inertne atmosfere u tankovima tereta, čime se opasnost od eksplozije smanjuje na najmanju moguću mjeru. Obveza ugradnje sustava inertnoga plina donesena je tek 1980-ih godina kao posljedica niza eksplozija na tankerima diljem svijeta uz gubitak mnogih ljudskih života [1, 2]. Brzina i kvaliteta inertiranja tankova ovisi o kapacitetu i izvedbi sustava inertnoga plina te geometriji tankova koji se ispunjavaju inertnim plinom. Inertiranje tankova tereta provodi se postupkom miješanja inertnoga plina s parama ugljikovodika ili postupkom istiskivanja para ugljikovodika iz tanka tereta.

Zbog niza utjecajnih uvjeta te kompleksnog strujanja fluida unutar tankova, analitičkim je postupcima vrlo teško izračunati vrijeme potrebno za kvalitetno inertiranje tankova tereta. Primjenom odgovarajućih numeričkih metoda moguće je predvidjeti tijek inertiranja tankova tereta uz zadane rubne uvjete poput okolišnih uvjeta, geometrije tanka, vrste inertnoga plina, njegove brzine i smjera strujanja na ulazu u tank, i sl. Takva saznanja mogu se iskoristiti pri projektiranju sustava inertnoga plina s namjerom da se u što kraćem vremenu postignu uvjeti koji osiguravaju maksimalnu sigurnost pri plovidbi ili manipuliranju teretom.

2. INERTNI PLIN I NJEGOVA PROIZVODNJA

Inertni plin je onaj plin koji pri zadanim uvjetima kemijski ne reagira s drugim tvarima. Poradi svojstva da ne reagiraju u kemijskim reakcijama, inertni se plinovi često rabe pri prevenciji nepoželjnih kemijskih reakcija. Inertni plin koji se najčešće koristi na brodovima mješavina je plinova sastavljena najvećim dijelom iz dušika, ugljičnog dioksida, kisika te manjih udjela vlage i dušikovih oksida. Takav sastav inertnog plina postiže se izgaranjem goriva u generatoru inertnoga plina ili dovodenjem ispušnih plinova iz dimovoda.

Na brodovima za prijevoz tekućih goriva i njihovih rafinata moglo bi se s najmanje troškova koristiti ispušne plinove koje proizvode po-

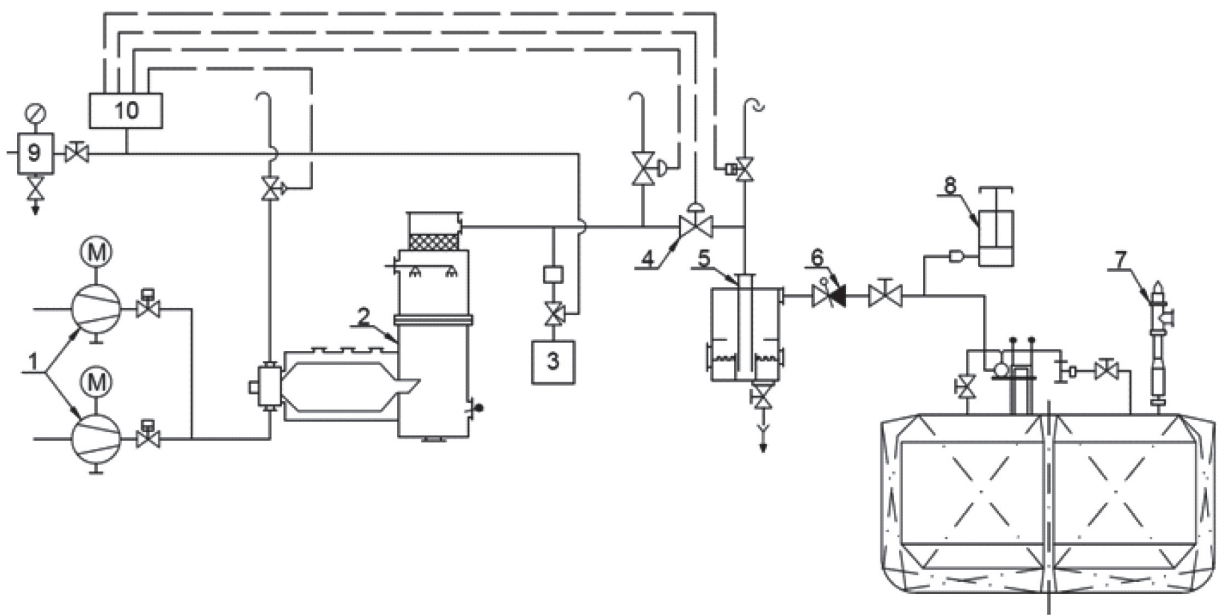
1 INTRODUCTION

Due to specific characteristics of liquid cargoes, there is a significant danger of explosion on board liquid cargo carriers. Such ships are equipped with inert gas systems which provide preservation of inert atmosphere inside cargo tanks, what decrease the danger of explosion on the smallest possibility. The installation of the inert gas system was imposed in early 1980's after several explosions on board VLCC tankers with severe loss of human lives [1, 2]. Quickness and quality of cargo tanks depend on the capacity and layout of inert gas system and geometry of cargo tanks being filled by inert gas. Cargo tank inerting is performed by mixing inert gas with hydrocarbon vapours (dilution process) or by the displacement of hydrocarbon vapours out of cargo tank. Due to many different factors and complex fluid flow inside cargo tanks, it is very difficult to calculate the time needed for quality cargo tank inerting by analytical methods. The application of adequate numerical methods provide prediction of cargo tank inerting progress by given boundary conditions such as environment conditions, cargo tank geometry, kind of inert gas, inert gas flow speed and inlet direction etc. Such information can be used during the inert gas system design process with the intention to create conditions for the highest safety during navigation or cargo handling in the shortest time.

2 INERT GAS AND ITS PRODUCTION

An inert gas is a gas which does not undergo chemical reactions under a set of given conditions. Because of that property, inert gases are frequently used for the prevention of undesirable chemical reactions. Inert gas which is commonly used on board ships is a gas mixture composed mostly of nitrogen, carbon dioxide, oxygen and small content of moisture and nitrogen oxides. Such composition of inert gas is obtained by fuel combustion in an inert gas generator or by taking exhaust gases from exhaust pipes.

The exhaust gases from liquid cargo carrier propulsion plants could be used with the lowest cost if their purity would be satisfactory and the oxygen content lower than the flammability limit. Although such a system is an economical solution for the inert gas production, it is not frequently used because such inert gas contains



Legenda:

- | | |
|-------------------------------|-------------------------------|
| 1 – ventilatori | 6 – nepovratni ventil |
| 2 – generator inertnoga plina | 7 – P/V ventil |
| 3 – analizer kisika | 8 – prekidač vakuumski ventil |
| 4 – regulacijski ventil | 9 – stanica instr. zraka |
| 5 – palubna vodena brtva | 10 – upravljačka jedinica |

Legend:

- | | |
|-------------------------|---------------------------|
| 1 – fans | 6 – non-return valve |
| 2 – inert gas generator | 7 – P/V valve |
| 3 – oxygen analyzer | 8 – P/V breaker |
| 4 – control valve | 9 – instrument air supply |
| 5 – deck seal | 10 – control unit |

Slika 1. Sustav inertnog plina s generatorom inertnog plina
Figure 1 Inert gas system with an inert gas generator

Izvor / Source: Autori / Authors

gonski strojevi kada bi njihova čistoća bila zadovoljavajuća, a sadržaj kisika ispod granice zapaljivosti. Iako je ovaj sustav ekonomično rješenje za dobivanje inertnoga plina, nije često korišten jer takav inertni plin, uz relativno visoke udjele kisika, sadrži i znatne količine nečistoća, čađe i sumporovih oksida [3].

U slučaju primjene strožih zahtjeva za kvalitetu inertnoga plina koristi se generator inertnoga plina, koji omogućuje proizvodnju inertnoga plina s niskim sadržajem kisika, sumporovih oksida, čađe i ostalih nečistoća. Generator, odnosno cijeli sustav za proizvodnju inertnoga plina prikazan je na slici 1. Ovakav sustav omogućuje proizvodnju inertnoga plina te njegovu distribuciju do tankova tereta uz regulaciju svih relevantnih parametara za pouzdan rad sustava.

relatively high oxygen content and considerable amount of impurities, soot and sulphur oxides [3].

In case of the application of rigorous requirements on inert gas quality, an inert gas generator is used, which provides a production of inert gas with low content of oxygen, soot, sulphur oxides and other impurities. An inert gas system scheme with inert gas generator is shown in Figure 1. Such a system provides inert gas production and its distribution to cargo tanks with the control of all relevant parameters for a reliable operation.

3. INERTIRANJE TANKOVA TERETA

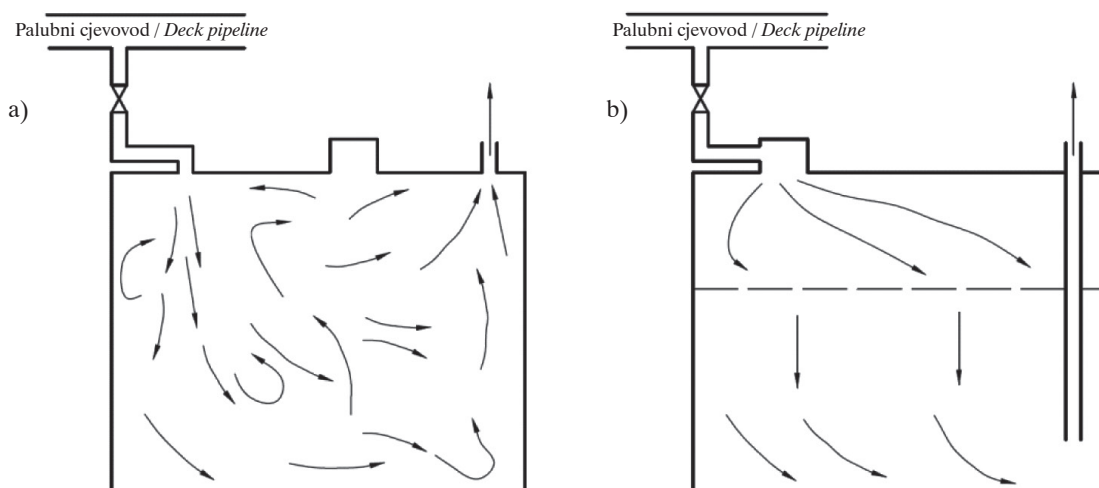
Pojam inertiranja tankova tereta podrazumijeva uvođenje inertnog plina u tankove tereta s ciljem smanjenja koncentracije para ugljikovodika i/ili smanjenja udjela kisika. Inertiranje tankova tereta može se izvoditi postupkom razrjeđivanja ili postupkom istiskivanja para ugljikovodika [4]. Pri postupku razrjeđivanja, pare ugljikovodika ili zraka se miješaju s inertnim plinom koji velikom brzinom ulazi u tank tereta te se njihova mješavina ispušta u atmosferu kroz otvor na vrhu tanka. Ovaj postupak inertiranja tankova je brži od inertiranja istiskivanjem. Tijekom inertiranja tanka potrebno je izmjeriti sadržaj kisika i para ugljikovodika na nekoliko različitih pozicija u tanku kako bi se s dovoljnom sigurnošću utvrdilo da ne prijete opasnost od eksplozije.

Inertiranje istiskivanjem podrazumijeva izmjenu sastava plinova u tanku tereta na temelju razlike gustoća inertnog plina, para ugljikovodika i svježeg zraka. Pritom su tankovi tereta opremljeni cijevima za inertiranje, a brzina uvođenja inertnog plina se održava dovoljno niskom kako bi se minimiziralo miješanje u tankovima (Slika 2.). Budući da je inertni plin manje gustoće od para ugljikovodika, zadržava se iznad para tereta i potiskuje ih prema dnu tanka. Prednost inertiranja potiskivanjem je mala potrebna količina inertnog plina te istovremeno inertiranje više tankova tereta.

3 CARGO TANKS INERTING

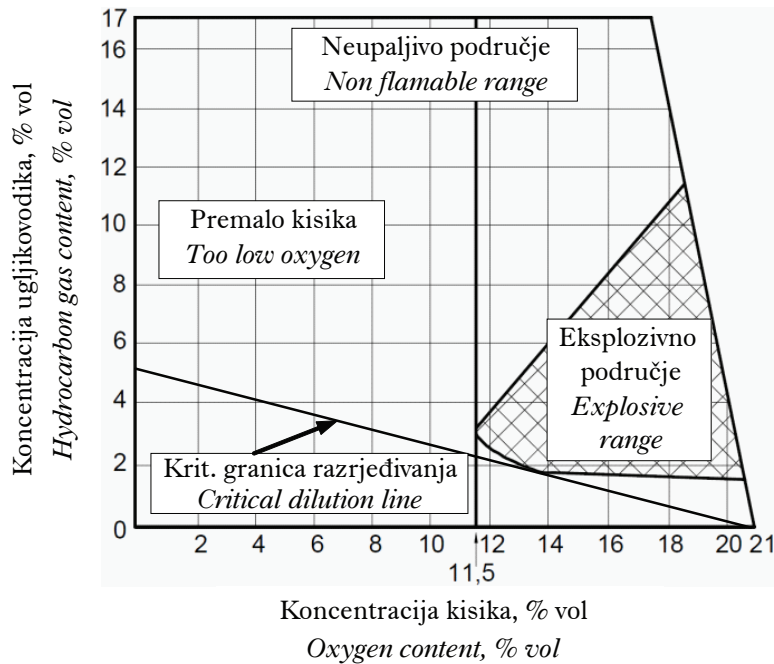
Cargo tanks inerting implies the introduction of inert gas in cargo tanks with the intention to lower the hydrocarbon vapour and/or oxygen concentrations. Cargo tanks inerting can be performed by the dilution process or by the displacement process of gas in cargo tanks [4]. During the dilution process, the hydrocarbon vapour or oxygen are mixed with the inert gas which enters the cargo tanks with high velocity and their mixture is exhausted in the atmosphere through the exhaust pipe on top of the cargo tank. This process is faster than the displacement process of gas in cargo tanks. During the cargo tanks inerting, oxygen and hydrocarbon vapour content must be measured on several different positions in order to safely ensure that there is no danger of explosion.

The displacement process implies the exchange of gas composition in cargo tanks on the basis of the difference between the densities of inert gas, hydrocarbon vapour and air. At the same time, cargo tanks are equipped with inerting pipes while the inert gas inlet velocity is maintained sufficiently low to minimize the mixing of gases inside cargo tanks (Figure 2.). Since inert gas has a lower density than hydrocarbon vapour, it retains over cargo vapours and presses them towards the tank bottom. The advantage of the displacement process is a small required volume of the inert gas what allows multiple cargo tanks to be inerted simultaneously.



Slika 2. Postupci inertiranja a) miješanjem i b) istiskivanjem
Figure 2 Inerting processes: a) dilution and b) displacement

Izvor / Source: <http://thenauticalsite.com/>



Slika 3. Dijagram eksplozivnosti smjese para ugljikovodika i kisika
 Figure 3 Explosive range of hydrocarbon vapour and air mixture

Izvor / Source: <http://thenauticalsite.com/>

Inertiranje tankova tereta se koristi pri sljedećim situacijama:

- Početno inertiranje tankova tereta nakon primopredaje broda ili nakon dokovanja;
- Obnavljanje zadovoljavajuće inertne atmosfere, ako je zbog nekog razloga kvaliteta inertne atmosfere u tankovima tereta bila narušena;
- Smanjenje koncentracije para ugljikovodika u tankovima tereta.

Kada se udio kisika u atmosferi tankova tereta snizi ispod 11,5 %, mješavina para ugljikovodika i zraka u tankovima više nije zapaljiva. Tank tereta može se smatrati inertnim ako je volumni udio kisika u atmosferi tanka niži od 8 % [5]. Dijagram na slici 3. prikazuje područje eksplozivnosti mješavine para zraka i ugljikovodika te su na njemu ucrtane karakteristične vrijednosti i točke područja eksplozivnosti.

4. NUMERIČKA SIMULACIJA INERTIRANJA TANKA TERETA

Numerička simulacija inertiranja tanka tereta provedena je na primjeru tankera za prijevoz sirove nafte nosivosti 47 000 tona. Izabrani tan-

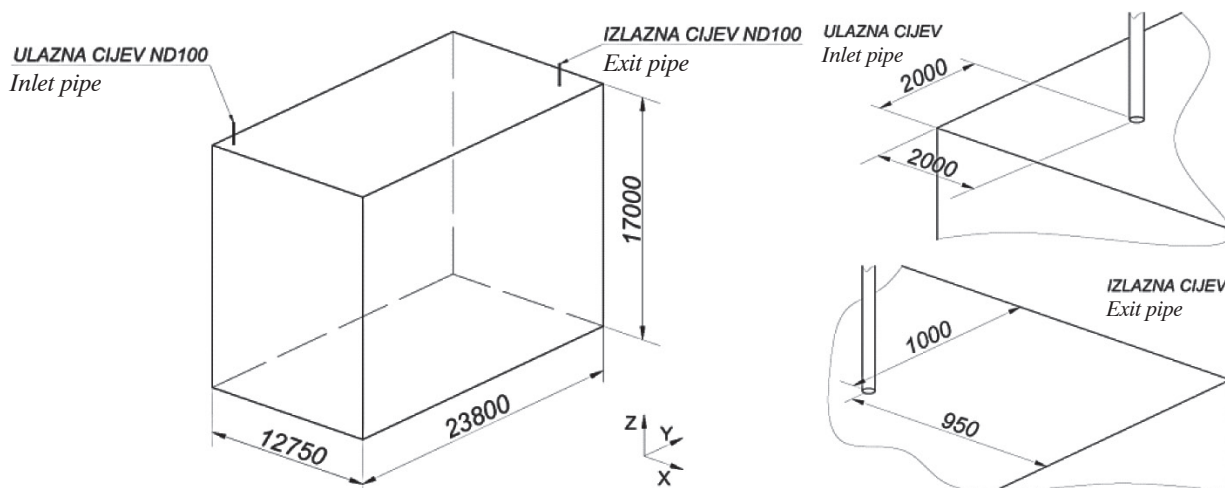
Cargo tank inerting is performed in the following conditions:

- Initial cargo tank inerting after the ship delivery or after docking
- Refreshment of the satisfactory inert atmosphere if its quality in cargo tanks was disturbed for some reason
- Reduction of the hydrocarbon vapours concentration inside cargo tanks.

When the oxygen content in cargo tanks is reduced below 11.5%, the mixture of the hydrocarbon vapour and air is no longer flammable. The cargo tank can be considered as an inert one when the oxygen content inside the tank is lower than 8% [5]. The explosive range of hydrocarbon vapour and air mixture with characteristic points and values is shown in Figure 3.

4 NUMERICAL SIMULATION OF CARGO TANK INERTING

The numerical simulation of cargo tank inerting is performed on the example of a crude oil carrier of 47,000 dwt. The chosen tanker has 12 cargo tanks or 6 pairs of cargo tanks where



Slika 4. Dimenzije tanka tereta te smještaj i dimenzije priključaka
Figure 4 Cargo tank dimensions with the location and size of fittings

Izvor / Source: Autori / Authors

ker ima 12 tankova, odnosno 6 pari tankova, te je za simulaciju izabran jedan od tankova obujma 5.158 m³. Na slici 4. prikazane su osnovne dimenzije tanka tereta te smještaj i dimenzije priključaka za ulaz inertnog plina i izlaz smjese para ugljikovodika i zraka. Inertiranje tankova tereta provodi se postupkom inertiranja miješanjem.

Radi pojednostavljenja geometrije unutrašnjosti tanka, izostavljena je uronjena pumpa tereta, zdenac ispod pumpe tereta, silazna cijev tereta i prateća armatura, a korigirane pregrade i krov tanka tereta predstavljeni su kao ravne glatke plohe.

Numerička simulacija provedena je s pomoću metode konačnih volumena te je izrađen trodimenzionalni model tanka tereta. Prostor, odnosno domena tanka tereta omrežena je nestrukturiranom mrežom tetraedara te su na modelu postavljeni odgovarajući rubni uvjeti.

Za analizu strujanja plinova unutar tanka tereta potrebno je definirati matematički model koji uključuje jednadžbe očuvanja mase, količine gibanja te očuvanja energije [6, 7].

Jednadžba očuvanja mase može se zapisati u sljedećem obliku:

$$\frac{\partial \rho}{\partial t} + \text{div}(\rho u) = 0, \quad (1)$$

gdje je ρ gustoća fluida, a u brzina strujanja kroz granice kontrolnog volumena.

simulation is performed on a 5158 m³ capacity tank. The main dimension of the cargo tank with the location and size of the inert gas inlet and gas mixture exhaust pipes are shown in Figure 4. The cargo tank inerting is performed by the dilution process.

Toward the simplification of the inside tank geometry, cargo pump, drop line and fittings were omitted, while the corrugated bulkheads and tank cover are represented as plain surfaces.

A numerical simulation was performed by applying a finite volume method and the cargo tank was represented by a three dimensional model. The cargo tank space was meshed with a non-structured tetrahedral mesh and adequate boundary conditions were set on the model.

To analyze the flow of gases inside the cargo tank, the mathematical model which includes mass, energy and momentum conservation equations had to be defined [6, 7].

The mass conservation equation can be written in the following form:

$$\frac{\partial \rho}{\partial t} + \text{div}(\rho u) = 0, \quad (1)$$

where ρ is the fluid density, and u the flow velocity through the control volume boundaries.

The momentum conservation equation can be written as:

Jednadžba očuvanja količine gibanja može se prikazati kao:

$$\frac{\partial}{\partial t}(\rho u_i) + \frac{\partial}{\partial x_j}(\rho u_i u_j) = -\frac{\partial p}{\partial x_i} + \frac{\partial \tau_{ij}}{\partial x_j} + \rho g_i + S_M, \quad (2)$$

gdje je p statički tlak, g ubrzanje sile gravitacije, S_M izvorni član kao posljedica djelovanja sila, a τ_{ij} tenzor viskoznih napreznja definiran kao:

$$\tau_{ij} = \mu \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) - \left(\frac{2}{3}\mu - \mu_v \right) \frac{\partial u_k}{\partial x_k} I_{ij}, \quad (3)$$

pri čemu su μ dinamička viskoznost, μ_v volumenska viskoznost, a I_{ij} jedinični tenzor.

Jednadžba očuvanja energije izražena je preko ukupne specifične entalpije h_0 :

$$\frac{\partial(\rho h_0)}{\partial t} + \text{div}(\rho h_0 u) = -p \text{div} u + \text{div}(k \text{grad} T) + S_h, \quad (4)$$

gdje je k koeficijent provođenja topline, a S_h izvorni član koji opisuje dotok topline. Ukupna specifična entalpija h_0 definirana je kao $h_0 = i + p/\rho + \frac{1}{2}(u^2 + v^2 + w^2) = E + p/\rho$, pri čemu je i unutarnja energija.

Za opis turbulentnog strujanja odabran je standardni k - ε model turbulencije koji je opisan s dvije transportne jednadžbe za opis kinetičke energije turbulencije k i energije disipacije turbulencije ε . Detaljni opis standardnoga modela turbulencije dan je u [7].

5. ANALIZA REZULTATA SIMULACIJA

U ovome radu simulacija inertiranja tanka provedena je za slučaj prvog inertiranja tanka nakon primopredaje broda ili inertiranja nakon dokovanja broda. Na početku simulacije, unutrašnjost tanka ispunjena je zrakom pri normalnim okolišnim uvjetima, a potom je u tank upuhivan plin dušik. Pretpostavljeno je da je dušik jednake temperature kao zrak u tanku tereta. Izmjena topline između stijenki tanka tereta i okoline je zanemarena.

Simulacija inertiranja tanka tereta provedena je za tri različita smjera upuhivanja dušika, a s ciljem istraživanja kako pojedini smjer utječe na brzinu postizanja inertne atmosfere. Analizirani smjerovi upuhivanja dušika prikazani su na slici 5. pri čemu je struja dušika usmjerena okomito prema dnu tanka (slučaj 1), u smjeru prostorne dijagonale (slučaj 2) te u smjeru dijagonale bočne stijenke tanka tereta (slučaj 3). Sve

$$\frac{\partial}{\partial t}(\rho u_i) + \frac{\partial}{\partial x_j}(\rho u_i u_j) = -\frac{\partial p}{\partial x_i} + \frac{\partial \tau_{ij}}{\partial x_j} + \rho g_i + S_M, \quad (2)$$

where p is the static pressure, g is the gravity, S_M is the source term as the consequence of force actions, and τ_{ij} is the viscous stress tensor defined as:

$$\tau_{ij} = \mu \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) - \left(\frac{2}{3}\mu - \mu_v \right) \frac{\partial u_k}{\partial x_k} I_{ij}, \quad (3)$$

where μ represents the dynamic viscosity, μ_v is the volumetric viscosity, and I_{ij} is the unit tensor.

The energy conservation equation is expressed by the total specific enthalpy h_0 :

$$\frac{\partial(\rho h_0)}{\partial t} + \text{div}(\rho h_0 u) = -p \text{div} u + \text{div}(k \text{grad} T) + S_h, \quad (4)$$

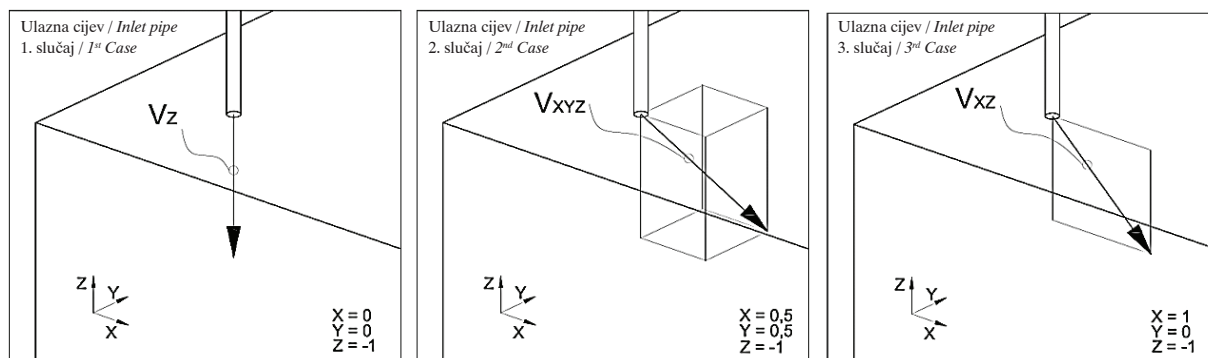
where k is the heat transfer coefficient, and S_h the source term which describes the heat flow. The total specific enthalpy h_0 is defined as $h_0 = i + p/\rho + \frac{1}{2}(u^2 + v^2 + w^2) = E + p/\rho$, where i is the internal energy.

The turbulent flow is described by the standard k - ε turbulence model which consists of two transport equations for the turbulent kinetic energy k and the dissipation of the turbulent kinetic energy ε . A detailed description of the k - ε turbulence model is given in [7].

5 SIMULATION RESULTS ANALYSIS

In this paper, the simulation of the cargo tank inerting was carried out for the case of the first inerting after the ship delivery or after the ship docking. At the beginning of the simulation, the cargo tank interior was filled with air at normal ambient conditions and nitrogen blow into the cargo tank started thereupon. It was assumed that the nitrogen temperature is equal to the air temperature inside the cargo tank. The heat exchange between the cargo tank walls and the ambient was neglected.

The cargo tank inerting simulation was carried out for three different nitrogen stream directions with the intention to investigate how certain stream directions influence on reaching the inert atmosphere. The analyzed stream directions are shown in Figure 5 where the nitrogen stream is aimed straight to the tank bottom (case 1), towards space diagonal (case 2) and towards cargo tank side wall diagonal (case 3).



Slika 5. Smjerovi upuhivanja dušika u tank tereta
 Figure 5 Nitrogen injection directions into the cargo tank

Izvor / Source: Autori / Authors

simulacije provedene su za brzinu strujanja dušika od 20 m/s.

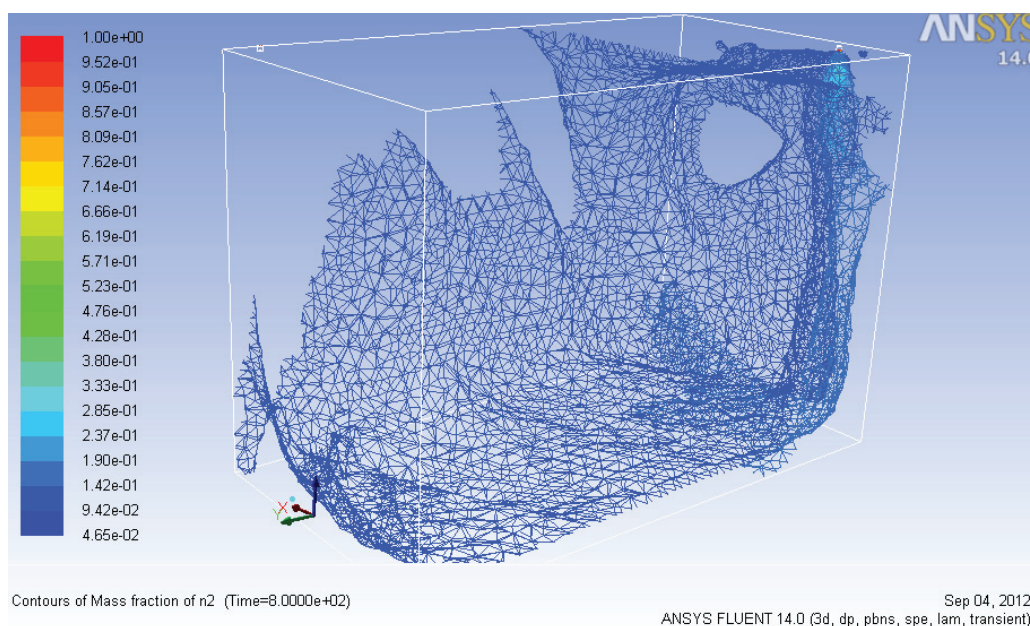
All simulations are carried out for the nitrogen stream velocity of 20 m/s.

5.1. Analiza inertiranja tanka za slučaj 1

5.1 Cargo Tank Inerting Analysis – Case 1

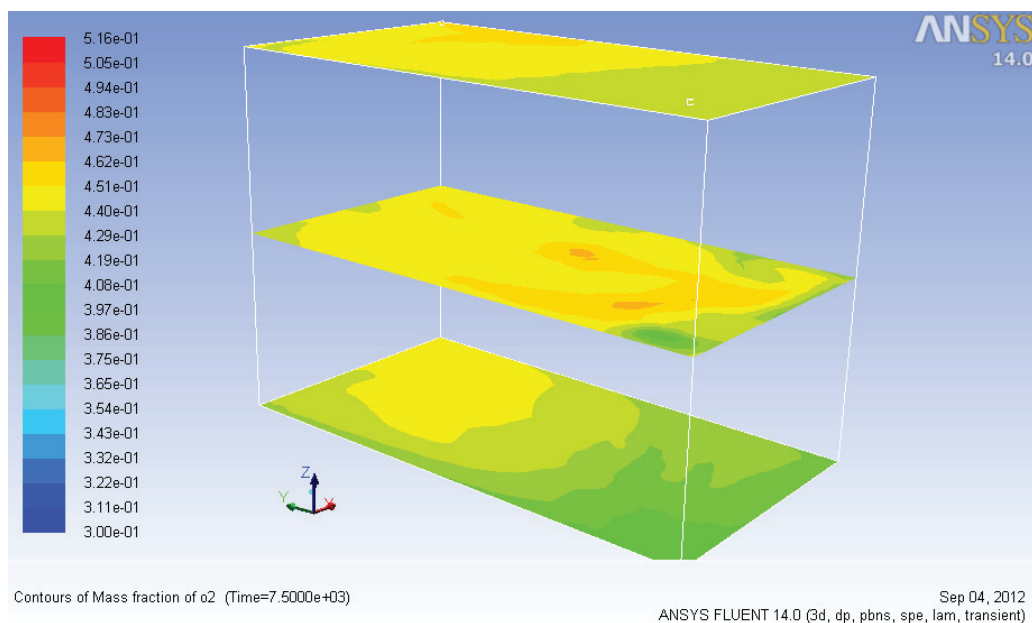
Numerička simulacija inertiranja tanka za slučaj 1 ukazuje da se dušik najprije rasprostiraju uzduž bridova i stijenki tanka te nakon 800 sekundi upuhivanja dušik još nije dosegao otvor izlazne cijevi (Slika 6.). Ovakav način upuhivanja dušika formira neku vrstu plašta koja okružuje središnju zonu tanka s većom koncentracijom zraka.

The numerical simulation of the cargo tank inerting for case 1 shows that nitrogen flows firstly along cargo tank edges and walls and did not reach the exhaust pipe 800 seconds after blowing into the tank (Figure 6). This mode of the nitrogen injection forms some kind of a jacket which surrounds the central zone of the tank with a higher concentration of the air.



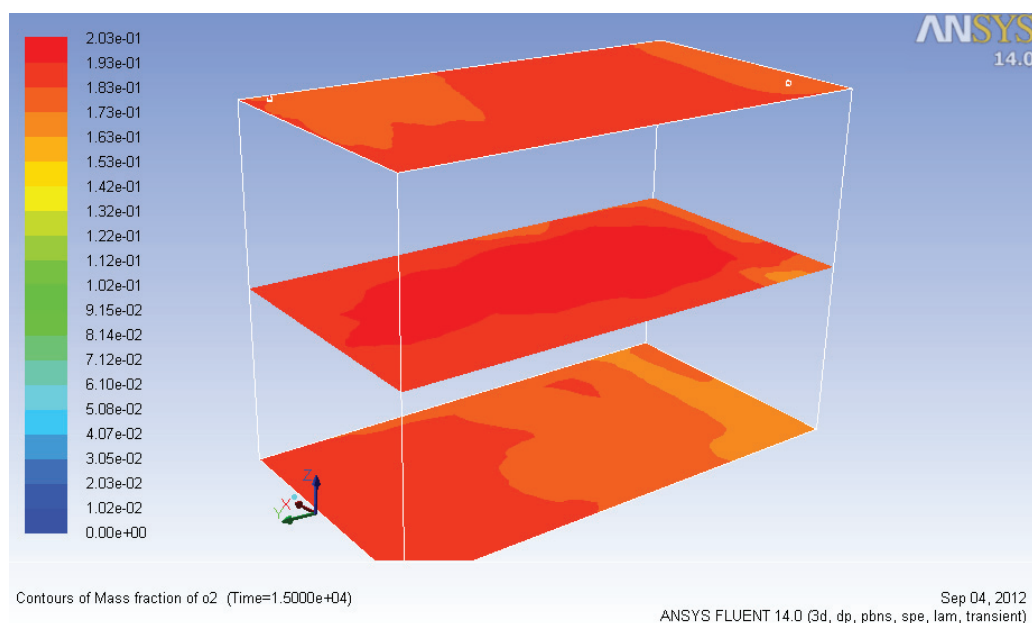
Slika 6. Koncentracija dušika nakon 15 minuta
 Figure 6 Nitrogen concentration after 15 minutes

Izvor / Source: Autori / Authors



Slika 7. Koncentracija zraka u tanku tereta nakon 2 h (vrh, sredina i dno tanka)
Figure 7 Air concentration after 2 hours (top, middle and bottom of the tank)

Izvor / Source: Autori / Authors



Slika 8. Koncentracija zraka u tanku tereta nakon 4 h (vrh, sredina i dno tanka)
Figure 8 Air concentration in the cargo tank after 4 hours (top, middle and bottom of the tank)

Izvor / Source: Autori / Authors

Smještaj cijevi te smjer upuhivanja imaju za posljedicu veće brzine strujanja uz rubove tanka, pa nakon što dušik ispuni sve rubove i kutove tanka tereta, središnja se zona relativno sporo razrjeđuje. Na slici 7. prikazana je koncentracija zraka u tanku nakon 2 sata od početka inertira-

The location of the inlet pipe and the injecting direction caused higher gas velocities along cargo tank edges and after the tank was filled with nitrogen, the central zone was relatively slowly diluted. Figure 7 shows the air content in the cargo tank after 2 hours of inerting which is

nja, a koja iznosi oko 50 %. Koncentracija zaostaloga zraka prikazana je u trima presječnim ravninama razmještenim na vrhu, u sredini i pri dnu tanka tereta. Središnja se zona najsporije razrjeđuje te nakon isteka puna 4 sata, prosječna koncentracija prvobitne atmosfere još uvijek iznosi 20 % (Slika 8.).

Promjene koncentracija zraka u tanku tereta tijekom cijele simulacije inertiranja prikazane su dijagramom na slici 8. za presječne ravnine na vrhu, sredini i na dnu tanka tereta. U skladu s trendovima dobivenih rezultata, za postizanje koncentracija zraka nižih od 10 %, uz ovakve uvjete upuhivanja dušika, trebalo bi još barem 1,3 h. Vrijednosti koncentracija zraka u gornjoj i donjoj zoni gotovo su identične, dok središnji dio ima nešto više vrijednosti, što je obrazloženo u tekstu iznad.

5.2. Analiza inertiranja tanka za slučaj 2

Smjer upuhivanja inertnoga plina u ovome je slučaju usmjeren prema središnjem dijelu tanka tereta te se već na samom početku inertiranja može očekivati intenzivnije miješanje i raspršivanje struje dušika. Struja dušika ne uspijeva doći do dna tanka, pa se dušik ne distribuira preko donjih rubova kao u prethodnom slučaju. U usporedbi sa slikom 6, uočljiv je nedostatak dušika u donjem desnom kutu tanka, a što je posljedica smjera upuhivanja dušika.

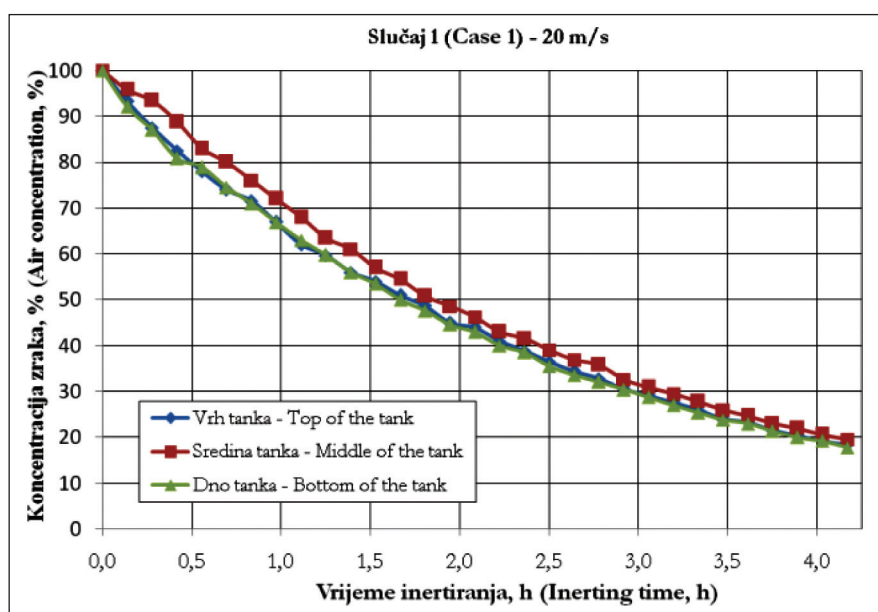
around 50%. The concentration of the retained air is shown in three section planes placed on top, in the middle and at the bottom of the cargo tank. The dilution of the middle zone is the slowest and the average concentration of the original atmosphere is still 20% after 4 hours of inerting (Figure 8).

The changes in the air concentration in the cargo tank during the whole simulation for the section planes on top, in the middle and at the bottom of the tank are presented in Figure 9. According to the trends of the obtained results and under such nitrogen blow conditions, the air concentration below 10% could be achieved in an additional 1.3 hours at least.

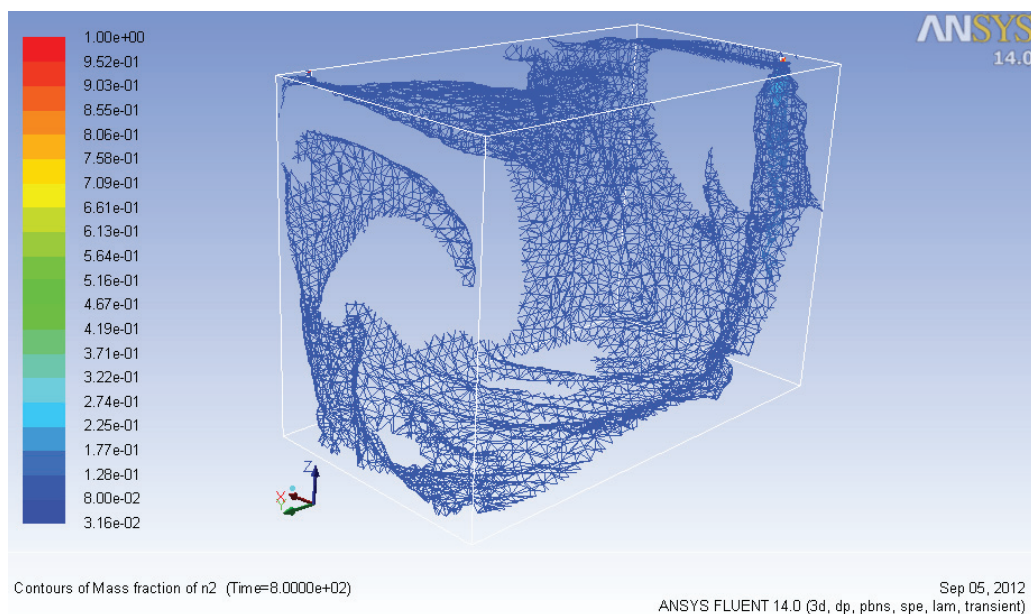
The values of air concentration on top and at the bottom of the tank are almost identical while in the middle of the tank the values are slightly higher as explained in the text above.

5.2 Cargo Tank Inerting Analysis – Case 2

In this case, the nitrogen injecting was directed towards the middle of the tank and a more intensive mixing and dispersion of the nitrogen stream could be expected immediately after the beginning of inerting. The nitrogen stream did not reach bottom of the tank and nitrogen was not distributed along the edges as in the previous case. As compared with Figure 6, the lack of

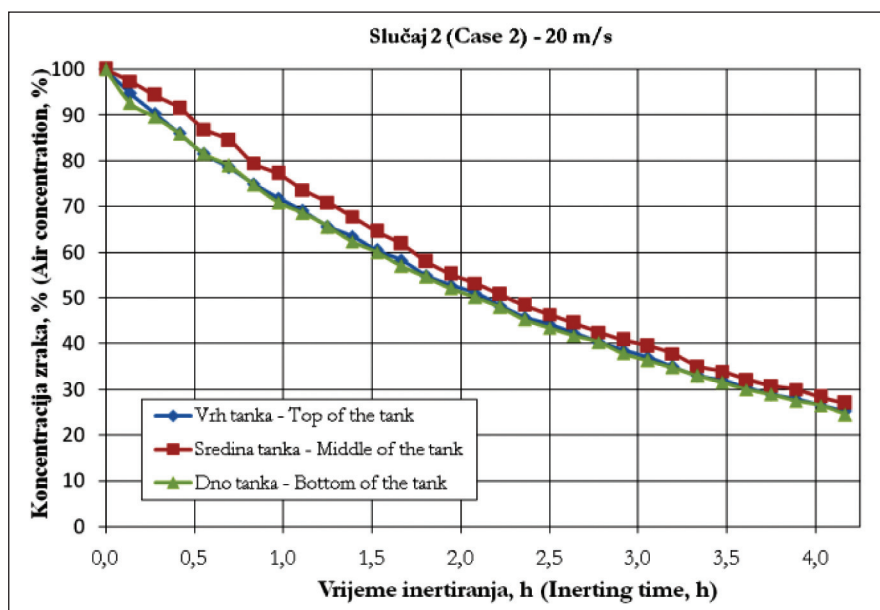


Slika 9. Promjena koncentracije zraka u ovisnosti o trajanju inertiranja
Figure 9 Change in the air concentration depending on the inerting duration



Slika 10. Koncentracija dušika nakon 15 minuta
Figure 10 Nitrogen concentration after 15 minutes

Izvor / Source: Autori / Authors



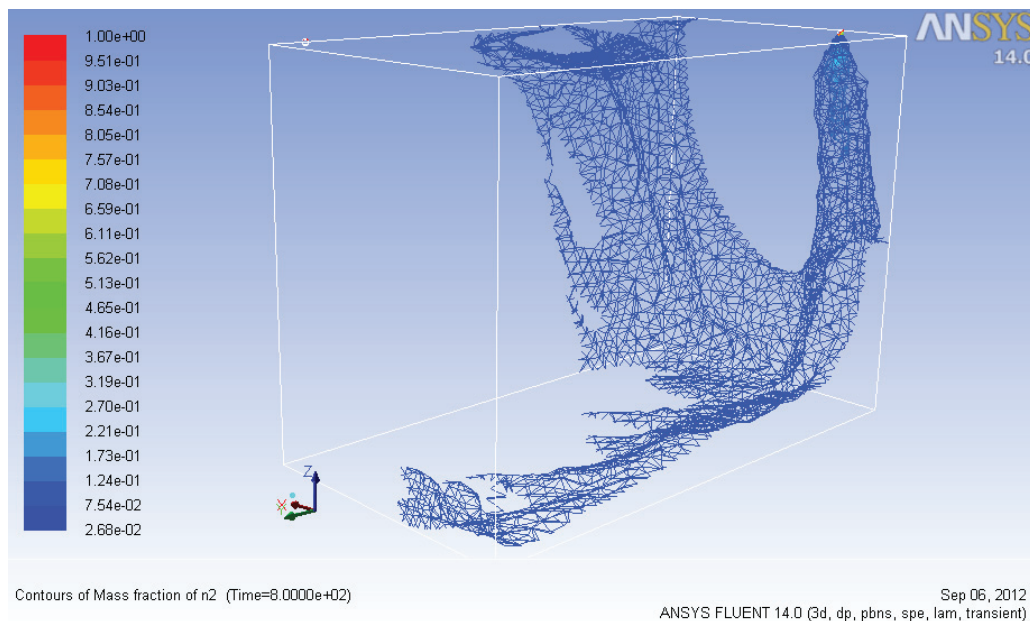
Slika 11. Promjena koncentracije zraka u ovisnosti o trajanju inertiranja
Figure 11 Change in the air concentration depending on the inerting duration

Izvor / Source: Autori / Authors

Distribucija dušika po rubovima tanka uspostavlja se tek nakon duljeg vremena, s time da u sredini tanka opet ostaje zona veće koncentracije zraka. Prosječna koncentracija zraka u tanku tereta smanjuje se sporije nego u slučaju 1 te će po isteku 4 sata inertiranja doseći vrijednost od oko 28 % u sredini tanka tereta (Slika 11.).

nitrogen in the lower right corner is noted as the consequence of the nitrogen injecting direction.

The nitrogen distribution along the cargo tank edges was established after a longer period whereby the middle of the tank still remained with a higher air concentration.



Slika 12. Koncentracija dušika nakon 15 minuta
Figure 12 Nitrogen concentration after 15 minutes

Izvor / Source: Autori / Authors

Ako bi se željela dostići koncentracija od 10 % zraka u tanku tereta, bila bi potrebna još skoro 2 dodatna sata inertiranja.

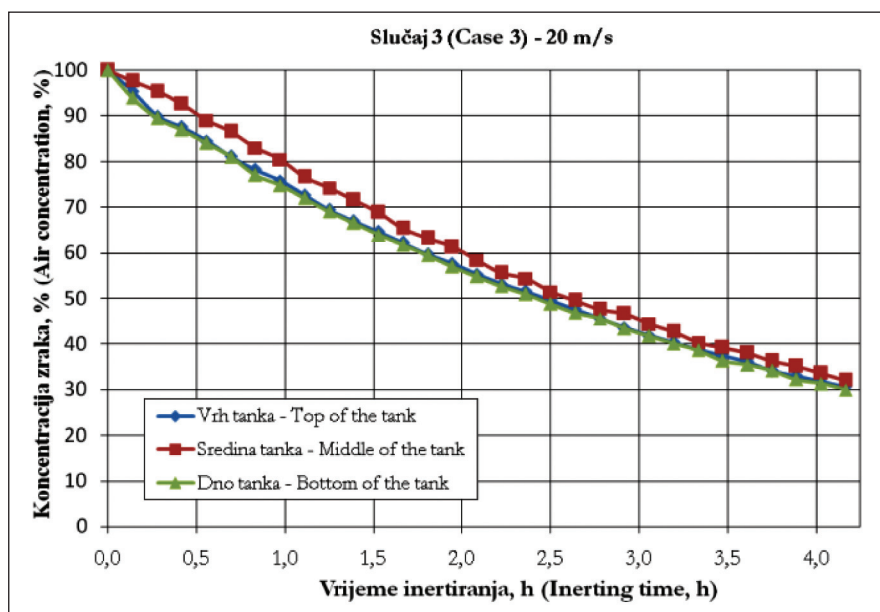
5.3. Analiza inertiranja tanka za slučaj 3

Ovim načinom upuhivanja dušika nastoji se postići bolji efekt ispiranja tanka te postupnije inertiranje tanka od ulazne prema izlaznoj cijevi. No, analizom dobivenih rezultata utvrđeno je da zbog velikih dimenzija tanka tereta mlaz dušika ne doseže suprotnu stranu tanka. Nakon 800 s inertiranja, minimalna koncentracija dušika iznosi 2,7 %, što je najmanje od svih triju analiziranih slučajeva. Distribucija dušika u tanku tereta nakon 800 s prikazana je na slici 12. Ovakav smjer upuhivanja nije ostvario željeni efekt i situacija je slična slučaju 2, ali sa slabijim učinkom. Na slici 13. prikazani su rezultati nakon 4 sata inertiranja, pri čemu prosječna koncentracija zraka u sredini tanka tereta iznosi oko 32 %.

The average air concentration was decreasing slower than in case 1 and its value was around 28% in the middle of the tank after 4 hours of inerting (Figure 11). To achieve the concentration of air in the cargo tank below 10%, inerting should be extended for an additional 2 hours.

5.3 Cargo Tank Inerting Analysis – Case 3

This mode of the nitrogen injection tends to achieve a better tank scavenging and progressive tank inerting from the inlet to the exhaust pipe. But, the analysis of the obtained results showed that the nitrogen stream did not reach the opposite tank side because of the large tank dimensions. After 800 s of inerting, the minimal nitrogen concentration was 2.7%, what is the lowest value of all the three analyzed cases. The nitrogen distribution in the cargo tank after 800 s is shown in Figure 12. This direction of the nitrogen injection did not achieve a desirable objective and the situation is similar to case 2, but with an inferior effect. Figure 13 shows the results after 4 hours of inerting where an average air concentration in the middle of the tank had a value of around 32%.



Slika 13. Promjena koncentracija zraka u ovisnosti o trajanju inertiranja
 Figure 13 Change in the air concentration depending on the inerting duration

Izvor / Source: Autori / Authors

5.4. Analiza inertiranja tanka uz povećane brzine strujanja

Od triju prethodno razmatranih slučajeva, pokazalo se da je slučaj 1 najefektivniji način inertiranja tanka tereta. Uz pretpostavku da bi povećanje brzine strujanja dušika ubrzalo inertiranje tanka, provedene su simulacije za brzine strujanja od 25 m/s i 30 m/s. Pritom je analiziran samo slučaj sa strujom dušika usmjerenom okomito prema dnu tanka, koji se je pokazao kao najbolji način inertiranja tanka.

Dobiveni rezultati prikazani su na slikama 14., 15. i 16. za svaku od triju karakterističnih zona u tanku tereta. Iz prikazanih dijagrama vidljivo je da se najbolje ispiranje, odnosno inertiranje tanka tereta postiže najvećom brzinom strujanja inertnoga plina, pri čemu se nakon 4 sata u tanku tereta postiže koncentracija zraka niža od 10 %. I ovdje se uočava podjednako dobro ispiranje gornje i donje zone, dok se u sredini tanka tereta uvijek zadržava nešto viša koncentracija zraka.

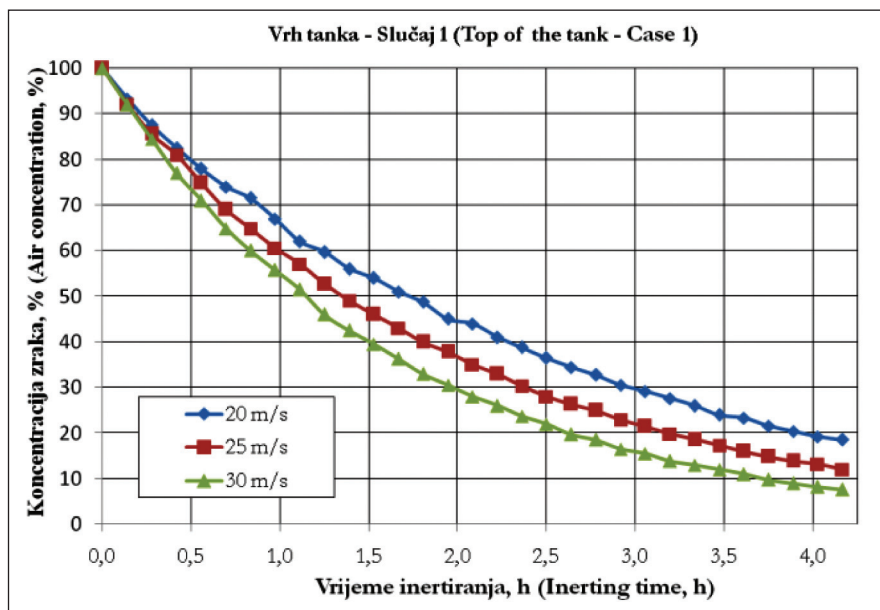
Prema preporukama iz literature [4], savjetuje se održavanje dovoljno visoke brzine strujanja inertnoga plina u tank zbog boljeg miješanja s medijem u unutrašnjosti tanka tereta. Također, ispusni otvor na tanku tereta mora imati dovoljno veliku površinu poprečnog presjeka kako pad tlaka na izlasku iz tanka ne bi

5.4 Analysis of Cargo Tank Inerting with Higher Stream Velocities

Among the three previously analyzed cases, case 1 approved as the most effective mode of cargo tank inerting. With the presumption that the increase in the nitrogen injection velocity would speed up the tank inerting, additional simulations for velocities of 25 m/s and 30 m/s were carried out. The case with the nitrogen stream aimed straight to the tank bottom was further analyzed because it approved as the most effective mode of cargo tank inerting.

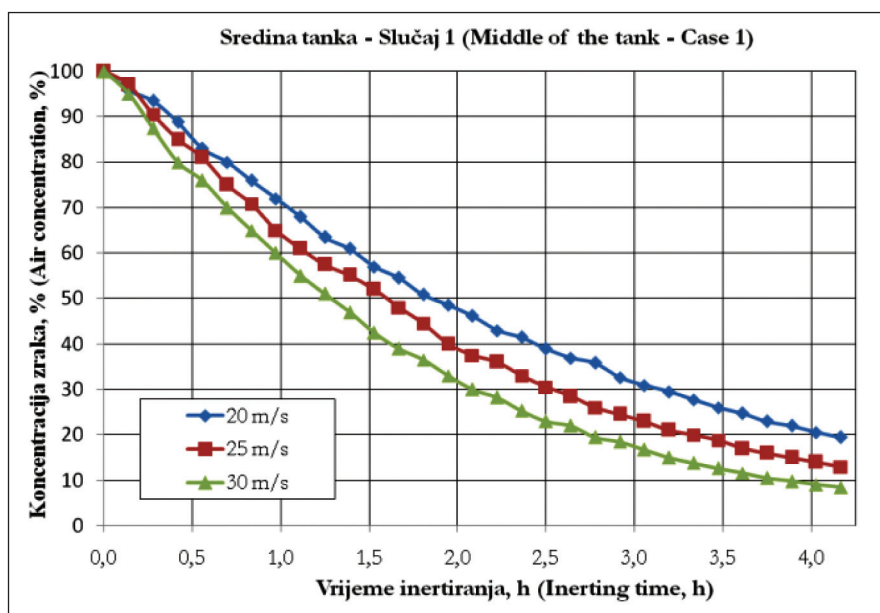
The obtained results are presented in Figures 14, 15 and 16 for each of the three characteristic zones in the cargo tank. The results presented show that the best cargo tank inerting was achieved by the highest velocity of the inert gas stream, when the air concentration in the cargo tank below 10% was achieved after 4 hours of inerting. It can be noticed that the top and the bottom of the tank were evenly scavenged while the middle of the tank always contained a slightly higher concentration of air.

According to reference [4], it is recommended to maintain high velocities of the inert gas due to a better mixing with the media inside the cargo tank. In addition, the exhaust opening on the cargo tank must be of a sufficient area so the pressure drop on the tank exit would not



Slika 14. Promjena koncentracija zraka u ovisnosti o trajanju inertiranja – vrh tanka
 Figure 14 Change in the air concentration depending on the inerting duration – top of the tank

Izvor / Source: Autori / Authors

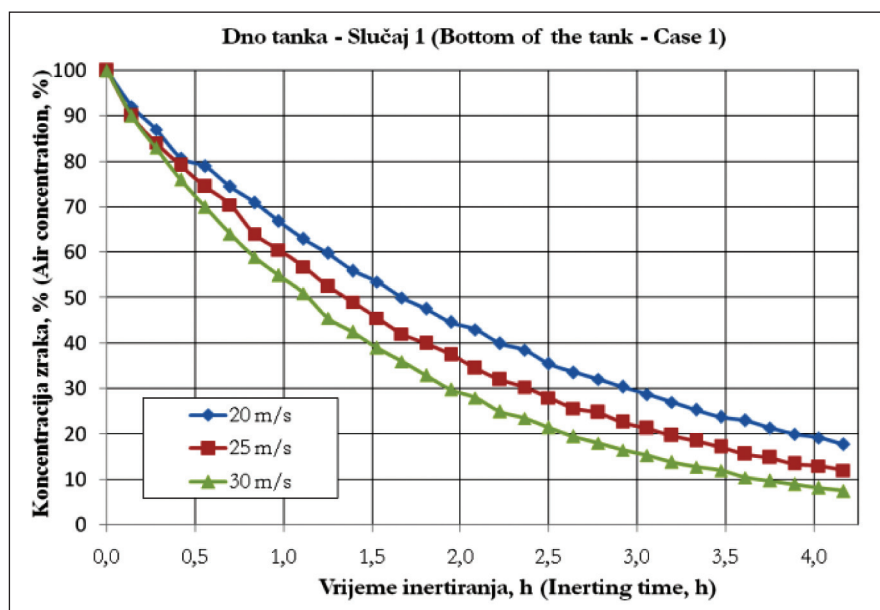


Slika 15. Promjena koncentracija zraka u ovisnosti o trajanju inertiranja – sredina tanka
 Figure 15 Change in the air concentration depending on the inerting duration – middle of the tank

Izvor / Source: Autori / Authors

bio prevelik, što bi nepovoljno utjecalo na smanjenje brzine strujanja upuhivanja inertnoga plina. Ovisno o kapacitetu sustava inertnoga plina na brodu, potrebno je voditi računa i o broju tankova koji se istodobno inertiraju, jer će to također imati značajan utjecaj na duljinu trajanja postupka inertiranja.

become too high what can decrease the velocity of the inert gas injecting. Depending on the inert gas system capacity, the number of tanks which are simultaneously inerted has a notable influence on the duration of the inerting process.



Slika 16. Promjena koncentracija zraka u ovisnosti o trajanju inertiranja – dno tanka
 Figure 16 Change in the air concentration depending on the inerting duration – bottom of the tank

Izvor / Source: Autori / Authors

6. ZAKLJUČAK

U radu je prikazana problematika inertiranja tankova na brodovima za prijevoz tekućeg tereta kao zaštita od eksplozije ili nastanka požara. Na kvalitetu inertiranja, odnosno ispiranja tankova tereta utječe niz čimbenika poput geometrije tanka tereta, sastava smjese plinova u tanku, vrste plina za inertiranje, brzine i smjera strujanja plina za inertiranje, temperature okoline itd. Uz pomoć numeričke simulacije dobiveni su rezultati koji mogu pomoći pri odabiru optimalnih parametara za inertiranje tanka. U radu su analizirana tri slučaja upuhivanja dušika u tank tereta, pri čemu je smjer struje dušika bio usmjeren okomito prema dnu tanka, u smjeru prostorne dijagonale te u smjeru dijagonale bočne stijenke tanka tereta. Upuhivanje dušika okomito prema dnu tanka pokazalo se kao najbolji postupak koji daje najbolje rezultate od svih analiziranih slučajeva. Također, kao što je i očekivano, najveća brzina upuhivanja inertnoga plina omogućuje najbrže i najkvalitetnije inertiranje tanka tereta.

Ovu numeričku simulaciju moguće je proširiti i za druge režime rada, pri čemu se posebno zahtjevni uvjeti rada za sustav inertnoga plina pojavljuju tijekom iskrcanja tereta kada inertni plin mora nadomjestiti obujam ispumpanog tereta. U tom slučaju u model je potrebno ugra-

6 CONCLUSION

The issue of the cargo tanks inerting as a protection from explosion or fire on board liquid cargo carriers is presented in this paper. The quality of cargo tanks inerting or scavenging is affected by a number of factors such as cargo tank geometry, gas mixture composition inside the tank, kind of the inert gas, velocity and direction of the inert gas stream, ambient temperature etc. The numerical simulation provided results which could help in the selection of optimal parameters for tank inerting. Three cases of the nitrogen injection were analyzed where the nitrogen stream was aimed straight to the tank bottom, towards the space diagonal and towards the cargo tank side wall diagonal. Furthermore, and as expected, the highest velocity of the inert gas injecting provides the fastest and the best cargo tank inerting.

This numerical simulation is possible to widen on other working regimes where particularly demanding working conditions appear during the cargo unloading when the inert gas must replace the volume of the pumped liquid cargo. In that case, the properties of the hydrocarbon vapours and diesel oil combustion gases should be added to model what will affect on the flow pattern and progress of the cargo tank inerting. An additional problem is the design of cargo

diti svojstva para ugljikovodika i inertnoga plina nastalog izgaranjem lakog dizelskog goriva, što će utjecati na profil strujanja i tijek inertiranja tanka. Dodatni problem predstavlja konstrukcija tankova tereta koji nemaju glatku unutrašnjost, pri čemu rebra i ostali dijelovi brodske strukture predstavljaju prepreke za nesmetano strujanje inertnog plina koji se upuhuje.

Bez obzira na gore navedene poteškoće, numeričke simulacije ovoga tipa mogu pružiti korisna saznanja o strujanju fluida unutar tankova tereta te dati uvid u očekivani tijek procesa inertiranja. Kvalitetna inertna atmosfera u brodskim tankovima tereta od velike je važnosti za sigurnost posade, broda i tereta te ova činjenica predstavlja stalnu motivaciju za prikupljanje novih saznanja iz ove problematike.

tanks which have not a smooth interior, while frames and other parts of the ship structure represent obstacles to the inert gas flow.

Regardless of the above mentioned difficulties, the numerical simulations can provide useful information on the fluid flow inside cargo tanks and give us an insight into the expected progress of the inerting process. A quality inert atmosphere in the ship cargo tanks is very important for safety of the crew, the ship and the cargo and this fact represents a permanent motivation for collecting new discoveries on this topic.

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