PROOF OF CONCEPT FUND

ARIES Proof-of-Concept Project

Development of hybrid electron accelerator system for the treatment of marine diesel exhaust gases

FINAL REPORT

April 2021

Partners:

1. Riga Technical University – RTU (Riga, Latvia) – Project leader
2. Institute of Nuclear Chemistry and Technology - INCT (Warsaw, Poland)
3. The European Organization for Nuclear Research - CERN (Geneva, Switzerland)
4. Fraunhofer Institute for Organic Electronics, Electron Beam and Plasma Technology - FEP (Dresden, Germany)
5. Remontowa Marine Design – Remontowa (Gdansk, Poland)
6. Milgravja Tehnoloģiskais Parks - Riga Ship Yard - RKB (Riga, Latvia)
7. BIOPOLINEX Sp. z o.o. (Lublin, Poland)

Advisors:

1. Italian Coast Guard – ITCG (Genova, Italy)
2. American Bureau of Shipping - ABS (Houston, USA)

The Final Report consists of the following integral parts which provide comprehensive overview of the ARIES Proof-of-Concept Project (PoC) "*Development of hybrid electron accelerator system for the treatment of marine diesel exhaust gases*":

- Project Summary and the main results
- Annex I: General Project Description
- Annex II: "*Report on operation of demonstrational pilot plant for hybrid treatment of flue gas from marine Diesel engine operated on ship berthed in Riga Shipyard*" – by INCT
- Annex III: "*Economic Report - comprehensive business, economic and financial analysis*" – by Biopolinex
- Annex IV: T. Torims et al., "*Development of a Hybrid Electron Accelerator System for the Treatment of Marine Diesel Exhaust Gases*", presented at the 11th Int. Particle Accelerator Conf. (IPAC'20), Caen, France, May 2020, paper THVIR14.
- Annex V: Y. Sun et al., "*Organic pollutant removal from marine diesel engine off-gases under electron beam and hybrid electron beam and wet scrubbing process*" in Proceedings NUTECH 2020, Warsaw, Poland, October 2020.
- Annex VI: A. Pawelec et al., "*Plasma technology to remove NOx from off-gases*" in Proceedings NUTECH 2020, Warsaw, Poland, October 2020.
- Project meetings and documentation https://indico.cern.ch/category/9244/
- Video: Presentation at the IPAC 2020 conference on the results of the ARIES Proof of Concept Project: https://www.youtube.com/watch?v=og5n7sr4umM
- Article by M. Vretenar: "*Cleaner cruises thanks to particle accelerators- Latvian tugboat provides first test-bed for new technology to clean exhausts from ships*", CERN, 7 August, 2019 https://home.cern/news/news/knowledge-sharing/cleaner-cruises-thanks-particle-accelerators
- Project data have been further analyzed in the Master Thesis:

  1. "*Impact on the Maritime Industry from an Introduction of a Hybrid Exhaust Gas Cleaning Technology*" developed by Mr. A. Ābele at Western Norway University of Applied Sciences. https://hvlopen.brage.unit.no/hvlopen-xmlui/handle/11250/2675486

  2. "*Qualitative and Quantitative Analysis of The Hybrid Electron Accelerator Exhaust Gas Abatement Technology Impact to the Selected Maritime Logistics Aspects*" developed Ms. E. Tskhay at RTU, Faculty of Computer Science and Information Technology.
- Final Project Report at the ARIES 4th Annual Meeting (virtual) 22/04/2021. https://indico.cern.ch/event/1008814/contributions/4285780/

Project summary

This project was envisaged to tackle the shipping industry's most pressing problem, its large-scale emissions of nitrogen oxides (NO_x), sulphur oxides (SO_x) and particulate matter (PM), by developing a hybrid exhaust gas-cleaning technology that combines an EB accelerator with improved wet-scrubbing technology. It is unique – in a single technological system – and addresses all three types of emissions simultaneously. It promises to be cheaper and more efficient than existing solutions. There are two main stages involved: 1) SO_2 and NO_x oxidation during the irradiation of wet gases by the EB from the accelerator and 2) the absorption of pollution products into an aqueous solution. For the very first time, test trials in a real maritime environment were conducted and attracted the interest of the maritime industry, policy makers and the accelerator community. The PoC has clearly confirmed the potential of this technology and forms a solid basis for the full-scale application of the hybrid system on sea-going ships. The results of this project are of the highest relevance to the accelerator community, as well as the maritime industry and policy makers.

Collaboration

The magnitude of this crucial societal challenge goes far beyond the capacity of any individual research institution or company and requires a wide collaborative effort. Therefore, under leadership of Riga Technical University, a multidisciplinary Collaboration of was summoned: partners with world-class expertise in accelerator and maritime technologies, shipping and economic assessments have joined this project to jointly offer a potential green shipping alternative for the maritime industry.

Virtue of this project is connection of two distinctive communities: maritime and accelerator. This is not merely scientific or technological undertaking by bringing particle accelerator on-board of the ship. Instead, it is opportunity for the accelerator community to understand compliances of the shipping industry and marine engineering as well as for maritime community to came in trust with the established accelerator research institutions and scientific community at large.

Commitment – this Collaboration through its multidisciplinary and multi-sectoral composition, itself clearly manifests feasibility of the hybrid system application on board of the ship. Importantly, its partners are contributing significantly to the development of the system by their own resources and this demonstrates interest, especially from the maritime community. Total budget of the PoC project was of ½ M EUR of which about 90% where direct contributions of partners themselves. This resulted in the great collaborative spirit of this Collaboration, multilateral trust and commitment to continue development of the hybrid technology until its full implementation of board of the ship up-to LTR6 and higher level of the technology readiness, which goes far beyond this pilot demonstration.

Engaging stakeholders. The best demonstration of the feasibility of the technology is by directly involving end users and relevant stakeholders in the very development of this promising system. Maritime community is very pragmatic and believes what it sees in real life with its own ayes. Naturally, the hybrid off-gas cleaning system development is push back of existing technological and acceptance boundaries. Therefore, Collaboration is engaging with European Commission, International Maritime Organisation, International Association of Classification Societies; Exhaust Gas Cleaning System Association, TIARA consortium and others. Italian Coast Guard and American Bureau of Shipping are directly participation in the Collaboration in the advisory capacity.

Objectives

Collaboration is aiming to proliferate particle accelerator technologies into the maritime domain by developing hybrid electron accelerator system for the treatment of marine diesel exhaust gases. This requires demonstration and validation of technology, thus providing the maritime industry with a much-needed innovative, cost-effective retrofit solution that would substantially improve environmental performance of fleets, by significantly reducing ship emissions. In order to achieve this green shipping goal and address existing challenges the project was tasked with the following pivotal objectives:

1. To conceptually proof the electron-beam accelerator application for the effective treatment of marine diesel exhaust gases.

2. To proof its technical feasibility within the real ship environment – advance technology to TRL3.

3. To demonstrate that the technology in question is capable to remove at the sufficient level SO_x a NO_x.

4. To provide sound financial evaluation on the cost-effectiveness of this technology.

5. To engage and inform all relevant stakeholders during the project.

Concept and experimental set-up

A fully operational tugboat "Orkāns" berthed at the pier of Riga Ship Yard was used as the source of flue gas. This ship is equipped with double two-stroke 450 kW Diesel engines. Outlet of the exhaust gas duct was flexibly connected to the accelerator complex by 320 mm pipe. In order to protect accelerator unit form potentially excessive gas temperatures, between ship and accelerator, a spray cooler was installed in the connecting pipeline. However, air curtain alone proved to be sufficient to fully protect the thin foil.

A mobile accelerator unit WESENITZ-II was used as an EB irradiation device. The device was originally designed for seed dressing and was optimised to flue gas treatment. Irradiation chamber is of rectangular cross section (120 x 1560 mm) and 1180 mm height. Gas flows vertically from bottom to top direction and is irradiated from both sides by use of two 125 kV EB accelerators. Maximal current for one accelerator is 100 mA. The single window with air curtain accelerators were applied in the device.

A counter current gas – liquid flow packed scrubber was selected as absorber for purpose of this project. The device of 1.2 m diameter and 5.5 m height was filled with *Bialecki* rings. Filling height was 2.6 m. A closed loop system was selected for water circulation in the scrubber. The circulating water was stored in two tanks filled with 3 m^3 of seawater. The water from the tanks was filtered and pumped to a system of nozzles located at the top of the scrubber and sprayed at the top of the filling, then flowed to the bottom of the device and back to the tanks by gravity. The gas from the irradiation unit was directed to the lower part of the scrubber and was released to the atmosphere by a stack located at the top of the device.

Water tanks were filled up with Baltic Sea water for the whole series of experiments in the close loop system configuration. In order to keep water ability for acidic gases absorption it's pH was kept over 7.5 by addition of sodium hydroxide. To enhance the oxidation potential and improvement of NO_x removal efficiency an oxidant ($NaClO_2$) was also added to the water. Total amount of oxidant was gradually increased up-to 10 kg.

Methodology

This demonstration was performed utilizing a mobile platform of the linear type of accelerator, directly connect to the ship exhaust duct. Crucial parameters of flue gas were measured: flue gas velocity, flue gas temperature and flue gas composition. An important factor influencing process is scrubber removal efficiency dependence on mass transfer, therefore high efficiency absorber shall be applied as the second stage of hybrid system. From among the generally accepted methods of considering the mass exchange process, in this case the most appropriate is to quantify the mass exchange process, including absorption efficiency. This value in a simple and transparent way allows to assess the impact of main process parameters on the effectiveness of gas treatment. It has been assumed that the absorption efficiency is a function of the following variables:

$$\eta = f(Ue, L/G, H, Co, Cr). \quad (1)$$

where η - absorption efficiency [%], *Ue* - gas velocity calculated on the empty column cross-section [m/s], *L/G* - spraying density of the absorption solution, litres of solution per cubic meter of gas [L/m^3], *H* – column packing height [m], *Co* - initial concentration of NO_x (calculated as NO_2) in the gas, [mg /m^3] or [vol %], *Cr* - concentration of the absorption solution, [kg/m^3] or [mass%].

Economic feasibility

A comprehensive economic and financial analysis was carried out by independent assessor Biopolinex, from the point of view of the end user and from the point of view of the manufacturer of the hybrid electron accelerator system for the exhaust gas treatment of marine diesel engines. The investment profitability was assessed on the basis of discounted cash flows, Net Present Value (NPV), Internal Rate of Return (IRR) and repayment period. The breakeven point was calculated. All was validated by a sensitivity analysis of the volatility of key financial parameters.

Measurements

The whole amount of flue gas generated by ship engine was treated in the system. The experiments were realized for three engine loads (0% - idling run, 50% and 100%). The flue gas sampling points were located up stream of the accelerator, exit of the scrubber and at the gas outlet stack. In this way gas composition was measured at the inlet of the installation, after irradiation and after treatment at the outlet of the plant. Moreover, five temperature measurement points - downstream of engine, upstream spray cooler, irradiation unit gas inlet, scrubber inlet and scrubber gas outlet - and one for gas velocity measurement point, before irradiation, were installed.

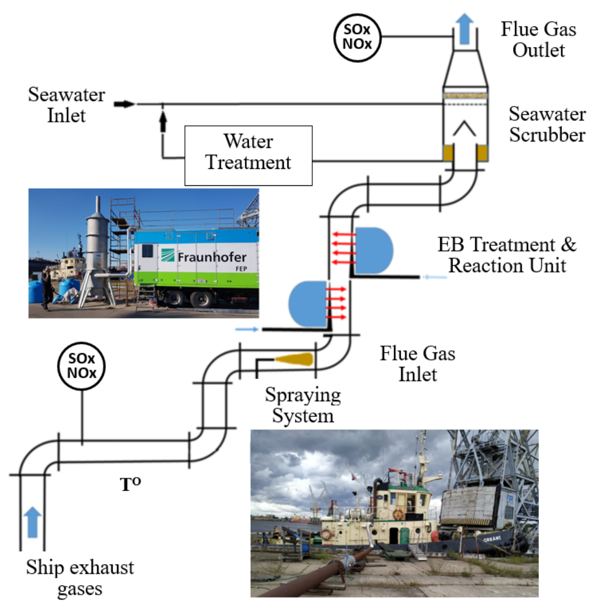


Figure 1: Hybrid Electron Accelerator System.

Main results

Engineering. The most important achievement of the PoC was technical integration of the diesel engine working upstream with the accelerator process chamber where titanium foil was protected by an air curtain and wet scrubber at downstream. The flow of flue gases was induced by diesel engine over pressure, which induced proper gas flow against pressure drop at all process installation components. Accelerator complex and protection windows with titanium foils were not damaged by high temperature off-gas flow. Earlier lab experiments were successfully validated, and the analytical methods were tested. This successful operation of ship-port based installation verified the assumptions that are the fundamental for the continuation of the project of the full on-board system development.

Collaboration. Commitment and dedicated efforts of the core team of this Collaboration, despite all challenges and technical difficulties, allowed to achieve remarkable results and proof the feasibility of the technology in question. All objectives set for the PoC were achieved and even exceeded. Most importantly, the collaborative effort demonstrated that the two underlying technologies for the envisaged system (accelerators and scrubbers) can be combined in real maritime environment - reaching TRL 3 - and can be instrumental for the green shipping policy.

Conclusions

Economic analysis confirmed profitability of the hybrid technology vis-à-vis Heavy Fuel Oil (HFO) option with the conventional scrubber off-gases abatement costs. This is true for both optimistic and optimal financial risk associated scenarios, indicating the high market potential of the maritime application of the hybrid technology.

Abatement of NO_x and SO_x. Although, the environmental and operational restrictions of port area allowed only for the usage of desulfurized (eventually SO_x free) marine diesel fuel, even with non-homogeneous and moderate irradiation dose, significant reduction up-to 45,8% of NO_x was recoded (see selected results in Table 1 and overall in Fig.2 and Fig.3.). This was matched with the measurement profile of other parameters of exhaust gases family measurements and matched with the analytical and prior lab trials. Very good agreement was observed, and this allowed to affirmatively prognose the significant reduction of SO_x in case of full scale on-board system operating on HFO case.

Table 1: Removal efficiencies of the NO and NO_x

Engine load	%	0	50	100
Oxidant concentration	mg/l	0	1	3,3
Gas flow rate	Nm^3/h	3316	4751	4915
Gas T at accelerator inlet	°C	51	136	124
Dose	kGy	4,1	5,7	5,5
Inlet concentration	NO, ppm	95	252	298
	NO_x, ppm	110	271	317
Remowal rate	NO, %	81,8	57,4	65,2
	NO_x, %	38,8	38,0	45,8

The NO_x removal was examined for different engine loads and different concentrations of oxidant.

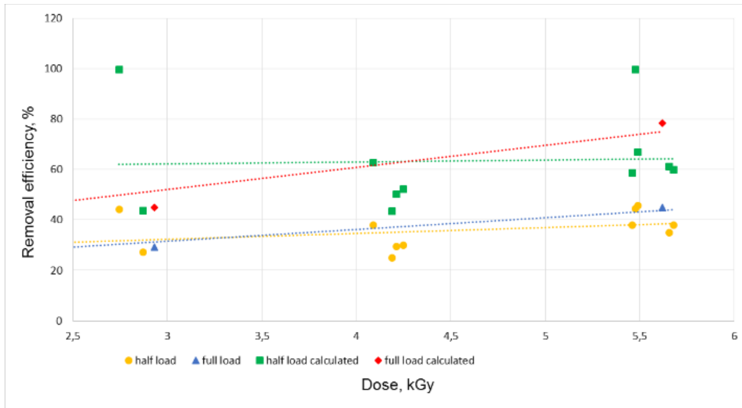


Figure 2. Dose dependence of NO_x removal efficiency for 50% and100 % engine load.

The increase of oxidant concentration in the process water in the scrubber has strong positive impact on NO_x removal efficiency.

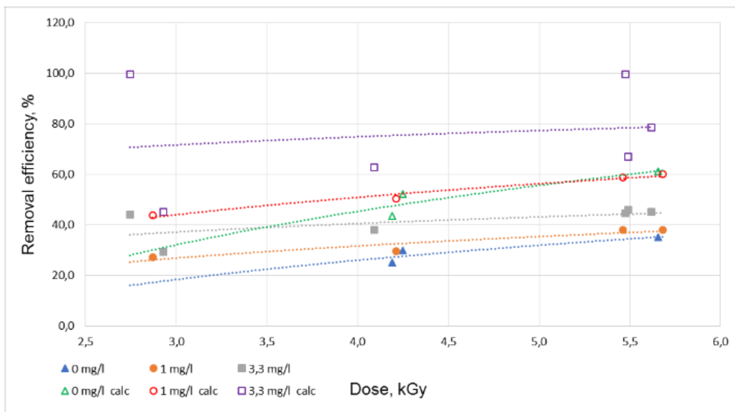


Figure 3. Dose dependence of NO_x removal efficiency for different concentrations of oxidant.

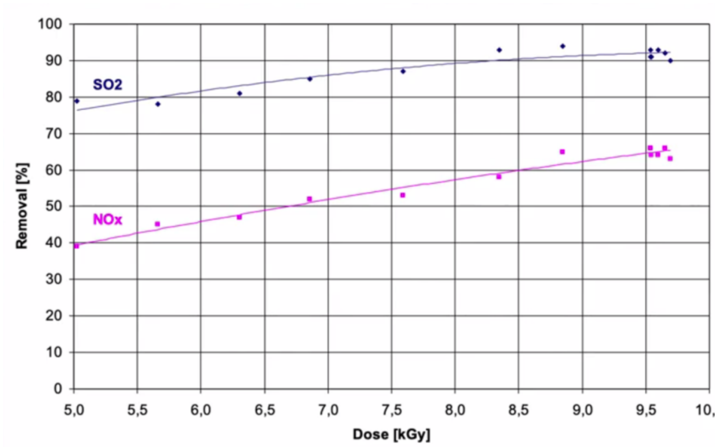


Figure 4. Dose dependence of SO_2 and NO_x matched with previous laboratory tests.

Abatement of gaseous organic pollutants

During the pilot test for pollutants removal from ship emission at Riga Ship Yard, organic pollutants before and after treatment were sampled and collected. They were transported to INCT laboratory for analysis. Subsequently organic pollutant removal under EB and EB hybrid wet-scrubbing process was studied. Gaseous organic pollutants, mainly VOCs, were collected at three different sampling points: before irradiation vessel, after irradiation vessels, and after wet-scrubber unit. They were collected with glass sampling bottles, Tedlar bags, Coconut Shell Charcoal (CSC) sorbents and XAD-2 sorbents according to US EPA method 18. A GCMS-QP5050 analyzer was used for analysis. Standard solutions, such as: AK-102.0-NAS-10X standard, M-502-REG and AK-101AA-ARO standard were used for making calibration curves. For the off-gases sampled using Tedlar bags and glass bottles, 500 microliter sampling gas was directly injected into the GC-MS analyzer. For the off-gases adsorbed by the sorbents, 10 ml CH_3OH (HPLC purity) and CH_3OH/CH_2Cl_2 (1:1, HPLC purity) were used to extracted VOCs from CSC and XAD-2 sorbents, respectively. List of organic compounds effectively adsorbed by Coconut Shell Charcoal sorbents and XAD-2 sorbents and detected (GC MS) at ship off gases and at other points of flue gases stream. Removal efficiency for organic pollutants is presented in Table 2.

Table 2. List of removal efficiency of organic compounds after EB and EB with wet-scrubber process

Compound	**Ship emission**	**Removal efficiency (after EB)**	**Removal efficiency (after EB with wet scrubber)**	**PEL*(mg/m^3)**
Toluene	1.04 mg/m^3	70.8% (0.304mg/m^3)	83.2% (0.175 mg/m^3)	37
Nitropropanone, $C_3H_5NO_3$, $CH_3COCH_2NO_2$	+	100%	100%	
1-Butene, 3-nitro-, $C_4H_7NO_2$, $CH_2=CHCH(CH_3)NO_2$	+	100%	100%	
Methyl butyrate, $C_5H_{10}O_2$, $C_3H_7COOCH_3$	+	100%	100%	
Chlorotoluene, C_7H_7Cl	+	100%	100%	250
Butoxyethoxyethyl acetate, $C_{10}H_{20}O_4$	+	89.7%	100%	
Dodecane, $C_{12}H_{26}$	30.63 µg/m^3 (0.004 ppm)	79.59% (6.25 µg/m^3)	100%	
Pentadecane, $C_{15}H_{32}$	10.13 µg/m^3	100%	100%	
Hexadecane, $C_{16}H_{34}$	57.96 µg/m^3 (0.006 ppm)	54.71% (26.25 µg/m^3)	97.79% (1.28 µg/m^3, 0.13 ppb)	
Heptadecane, $C_{17}H_{34}$	10.72 µg/m^3	100%	100%	
Octadecane, $C_{18}H_{38}$	38.05 µg/m^3 (0.003 ppm)	48.57% (19.57 µg/m^3)	92.01% (3.04 µg/m^3, 0.24 ppb)	
Hexadecane, 2,6,10,14-tetramethyl-, $C_{20}H_{42}$	+	100%	100%	
n-Eicosane, $C_{20}H_{42}$	9.60 µg/m^3	100%	100%	
Hexadecanoic acid, methyl ester, $C_{17}H_{34}O_2$	+	100%	100%	
Dibutyl phthalate, $C_{16}H_{22}O_4$, $C_6H_4(COOC_4H_9)_2$	+	7.50%	86.3%	5
Heneicosane, $C_{21}H_{44}$	13.31 µg/m^3	100%	100%	
Octadecanoic acid, methyl ester, $C_{19}H_{38}O_2$	+	100%	100%	
2,2-Dimethoxypropane, $(CH_3O)_2$-C-$(CH_3)_2$	+	100%	100%	
Methyl octanoate, $C_7H_{15}COOCH_3$	+	100%	100%	
Octanoic Acid, $C_7H_{15}COOH$	+	57.8%	100%	

Note: *PEL: Permissible exposure limits.

Pilot test in Riga shipyard shows that after 4.2 kGy EB irradiation, most organic pollutants have been removed from flue gas. Chlorotoluene and nitro compounds have been removed completely from gas phase, some aliphatic compounds (dodecane, hexadecane and octadecane) with high concentration still exist in the gas phase, their removal efficiency varies from 79.59 % for dodecane and 48.57 % for octadecane. After EB and wet scrubber treatment, most organic pollutants have been removed completely from flue gas, only trace amount of toluene (0.175 mg/m^3), hexadecane (0.13 ppb), octadecane (0.24 ppb) and dibutyl phthalate were present in the gas phase. Their removal efficiency could be further increased by increasing irradiation dose.

Way forward

Based on promising results of the PoC project and with the great support of stakeholders, maritime and accelerator partners, initial ARIES PoC partnership of Riga Technical University, Institute of Nuclear Chemistry and Technology, CERN, Fraunhofer Institute for Organic Electronics, Electron Beam and Plasma Technology, Remontowa Marine Design, Riga Ship Yard and Biopolinex has been considerably enlarged. This scientific and technological endeavour has grown into the full-fledged **HERTIS Collaboration** - **Hybrid Exhaust-gas-cleaning and Accelerator Technology for International Shipping (HERTIS).**

It is unprecedented and truly Europe trans-national and multi-disciplinary undertaking, linking together maritime and particle accelerator communities under umbrella of the scientific research: joint endeavour of 11 partners from 8 European countries. Leading research organisations – CERN and Fraunhofer FEP in the strong pan-European partnership with INCT, Riga Technical University and University of Tartu. Major shipping industry players – Grimaldi Group, American Bureau of Shipping, and Ecospray. Economical feasibility and business case is to be impartially evaluated by leading business expert KPMG supported by Biopolinex. Environmental impact assessment expertise and objectiveness is ensured by Western Norway Research Institute and University of Tartu.

Mission of HERTIS Collaboration is to pool resources and knowledge to work together based on coordinated Strategy, Activities and Projects related to development and implementation of the Maritime Hybrid Exhaust-gas-cleaning and Accelerator Technologies. With clear Strategic Goal, to contribute in meaningful and timely manner to:

- High-priority initiatives of the European Strategy for Particle Physics.
- Goals of the Strategy on Reduction of GHG Emissions from Ships of IMO.
- EU Green Deal Policy and related initiatives.

HERTIS Collaboration Objectives

- To develop and maintain joint Strategy and to undertake Activities in the common interest of Partners.
- To prepare and submit the Projects on behalf of the Collaboration.
- To create a strong and efficient exchange mechanism allowing creation of a common view and a joint platform.
- To exchange of up-to-date information among the partners and in one-voice vis-a-vis Stakeholders, Policy makers as well as Maritime and Accelerator Communities.
- To coordinate relevant research and technology development Activities.
- To foster multidisciplinary cooperation between Accelerator and Maritime Communities and generate new opportunities via joint Projects, contacts and events.

Annex I

PROOF OF CONCEPT FUND

Development of hybrid electron accelerator system for the treatment of marine diesel exhaust gases

By

RIGA TECHNICAL UNIVERSITY

Center of High Energy Physics and Accelerator Technologies

GENERAL PROJECT DESCRIPTION

Partners:

1. Institute of Nuclear Chemistry and Technology - INCT (Warsaw, Poland)
2. The European Organization for Nuclear Research - CERN (Geneva, Switzerland)
3. Fraunhofer Institute for Organic Electronics, Electron Beam and Plasma Technology - FEP (Dresden, Germany)
4. Remontowa Marine Design – Remontowa (Gdansk, Poland)
5. Milgravja Tehnoloģiskais Parks - Riga Ship Yard - RKB (Riga, Latvia)
6. BIOPOLINEX Sp. z o.o.(Lublin, Poland)

Advisors (see ANNEX 1 for supporting documents):

Annex I

1. Italian Coast Guard – ITCG (Genova, Italy)

2. American Bureau of Shipping - ABS (Houston, USA)

Background and Aims

Air pollution is an important issue among present day society, with people living in big cities at the greatest risk of harm. Despite the fact that air quality has been improved significantly in comparison to the last century, especially thanks to introducing of pollution control installations at the fossil fuel power boilers, there is still a lot of room for improvement. According to WHO (World Health Organization), more than 80% of people living in cities and towns are affected by the air pollution which exceeds safe norms set by WHO with countries of low economic status suffering the most from toxic pollutants. Recently, there has been significant concern with the pollution from marine sources which currently utilize low quality diesel fuels. As a result, research and development projects have focused heavily on creating cost effective technology that can clean off gases with a high level of efficiency.

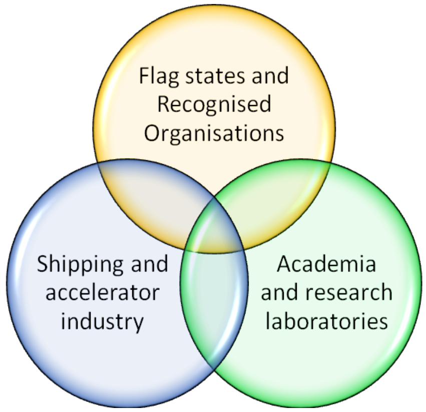
Exhausts from marine engines may contain nitrogen, oxygen, carbon dioxide and water vapor as well as nitrogen oxides, sulfur oxides, carbon monoxide, various hydrocarbons and complex particulate matter. The maritime transport usually uses heavy fuel oil (HFO) with a high content of sulfur, which naturally leads to the three main pollutants formation derived from shipping: nitrogen oxides (NO_X), sulfur oxides (SO_X) and particulate matters (PM). Around 15% of global NO_X and 5-8% of SO_X emissions are attributable to oceangoing ships. SO_2 and NOx emission as a smog component is a precursor to acid rains and it can have a negative influence on plant life as well as on wider ecosystems. Therefore, it is necessary to use a gas purifying method before releasing them into the atmosphere. To address the adverse impacts of sulfur and nitrogen oxides from shipping emission, the maritime sector is required to find highly efficient and low cost methods of gaseous pollutants removal. According to International Maritime Organization regulations (MARPOL Annex VI), there are two sets of emission and fuel quality requirements: global (progressive reduction in globally emissions of SOx, NOx and particulate matter) and more restrictive requirements dedicated to ships in deliberately established zones – Emission Control Areas (ECA). Outgoing methods are applied to remove NO_X or SO_2 separately. These technologies are divided into NO_X-reducing devices and SO_X scrubbers and their development is focused on process engineering aspects of such systems, including designing of apparatus, main dimensions, advantages/disadvantages as well as processes economy and cost analysis. The removal of nitrogen oxides is a difficult process, requiring the use of expensive catalysts. However, as international emissions regulations on nitrogen and sulfur oxides tighten, current removal methods are becoming increasingly insufficient. First of all, marine's scrubbing and denitration systems are expected to be compatible. NO_X reducing systems usually requires a high temperature of activation, close to 300^o C. Simultaneously, SO_2 solubility decrease at higher seawater temperatures. For this reason, equipment manufacturers are expected to provide guidance on the maximum sulfur content of fuel that can be consumed by an engine or boiler with a scrubbed exhaust, so that emissions remain within applicable limits, together with any seawater temperature limitations that may apply and, if applicable, the engine's NO_X certification limits. The main challenges for marine SCR applications are sulfur originated catatlyst deactivation resistance and very low efficiency at temperatures feasible for SOx scrubbing.

Currently, SCR catalyst mainly relies on V_2O_5–WO_3–TiO_2, but V_2O_5 is a kind of highly poisonous material and the active temperature is above 300^o C. The mechanism for deposit formation involves an undesirable parallel reaction (to the NO_X conversion) at the catalyst whereby sulfur dioxide in the exhaust is oxidized to sulfur trioxide (SO_3), which can then react with ammonia (used as an reagent in pure or urea solution form) to form ammonium sulphate and bisulphate. Such a process reduce the effective area and shorten the lifespan of the catalyst, with fuel-related hydrocarbon and particulate matter adding to the fouling. The spent catalyst which has to be replaced each 5 – 6 years , is a hazardous solid waste. As conditions deteriorate, NO_X reduction is impaired and more un-reacted ammonia will slip past the catalyst. This system may reduce the emissions of NO_X by more than 90%, (obligatorily requires comparatively low-sulfur fuel), with cost effectiveness of 873.5 $/ton and SOx emissions by 98% with 3115 $/ton in case of using seawater scrubbing. Researchers have indicated that the urea consumption of SCR system is 8.5% of the consumption of diesel oil, which will surely have a significant influence on size and weight of installation. Therefore, it is necessary to look for new cost effective solutions to remove both nitrogen and sulfur oxides with high efficiency simultaneously.

New, **hybrid technology** is based on the concept of combining two methods used to clean up the exhaust gases: Electron Beam (EB) and Improved Wet Scrubbing. This hybrid technology has a great potential to solve the emerging problem of marine industry, although it still requires research. Taking under consideration all of the advantages of the technology in comparison to other available methods, hybrid technology may become a promising and cost-saving option in the future marine market.

This is multidisciplinary and multi-industry project involving important stakeholders as indicated below.

Annex I



Partners of the potential Consortium *inter alia* had two designated meetings where Project proposal was discussed in great detail:
1 December 2017 at CERN – https://indico.cern.ch/event/659434/
1 March 2018 in Genova at the premises of the Italian Coast Guard - https://indico.cern.ch/event/704222/

Participants

Lead Applicant **RIGA TECHNICAL UNIVERSITY - Centre of High Energy Physics and Accelerator Technologies – RTU -, 3341000709, established in KALKU IELA 1,** **RIGA 1658, Latvia, VAT number LV90000068977**		
Type of organization	**Country**	**ARIES Beneficiary**
University	Latvia	yes
Name of contact person	**Job title**	**E-mail**
Prof. Toms TORIMS	Director of the Center of High Energy Physics and Accelerator Technologies	toms.torims@rtu.lv

Partner #1 - Institute of Nuclear Chemistry and Technology – INCT - INSTYTUT CHEMII I TECHNIKI JADROWEJ (INCT), 001024020/0000098738, **established in ul. Dorodna 16, WARSZAWA 03-195, Poland, VAT number PL5250008330**		
Type of organization	**Country**	**ARIES Beneficiary**
Research institute	Poland	yes
Name of contact person	**Job title**	**E-mail**
Prof. dr hab. inż. Andrzej G. Chmielewski	General Director	A.Chmielewski@ichtj.waw.pl

Partner #2 - The European Organization for Nuclear Research - CERN -, N/A, established in ROUTE DE MEYRIN CERN, GENEVA 23 1211, Switzerland, VAT number N/A		
Type of organization	**Country**	**ARIES Beneficiary**
Research laboratory	Switzerland	yes
Name of contact person	**Job title**	**E-mail**
Matti Tiirakari	Senior Advisor	Matti.Tiirakari@cern.ch

Partner #3 - Fraunhofer Institute for Organic Electronics, Electron Beam and Plasma Technology – FEP - FRAUNHOFER GESELLSCHAFT ZUR FOERDERUNG DER ANGEWANDTEN FORSCHUNG E.V. (FEP) EV, VR4461, established in HANSASTRASSE 27C, MUNCHEN 80686, Germany, VAT number DE129515865		
Type of organization	**Country**	**ARIES Beneficiary**
Research institute	Germany	yes
Name of contact person	**Job title**	**E-mail**
Dr. Goesta Mattausch	Head of Department	goesta.mattausch@fep.fraunhofer.de

Partner #4 - Remontowa Marine Design –REMONTOWA Marine Design & Consulting Na Ostrowiu 1, 80-958 Gdańsk, POLAND		
Type of organization	**Country**	**ARIES Beneficiary**
Company	Poland	no
Name of contact person	**Job title**	**E-mail**
Michał Sienkiewicz	Head of Innovation & Development Department	M.Sienkiewicz@rmdc.rh.pl

Partner #5 - Milgravja Tehnoloģiskais Parks - Riga Ship Yard – RKB - Sabiedrība ar ierobežotu atbildību "Milgravja Tehnoloģiskais Parks", 40103713813, Gāles iela 2, Rīga, LV-1015, VATnumber LV40103713813		
Type of organization	**Country**	**ARIES Beneficiary**
Company	Latvia	no
Name of contact person	**Job title**	**E-mail**
Einars Buks	Chairman of the Board	einars.buks@riga-shipyard.com

Partner #6 - BIOPOLINEX Sp. z o.o., 0000345851, 20-417 Lublin, Władysława Kunickiego 45, Poland, VAT number 9462595328		
Type of organization	**Country**	**ARIES Beneficiary**
Company	Poland	yes
Name of contact person	**Job title**	**E-mail**
Andrzej Pryzowicz	Representative	andrzej.pryzowicz@plus.lublin.pl

Technical Summary

Objectives

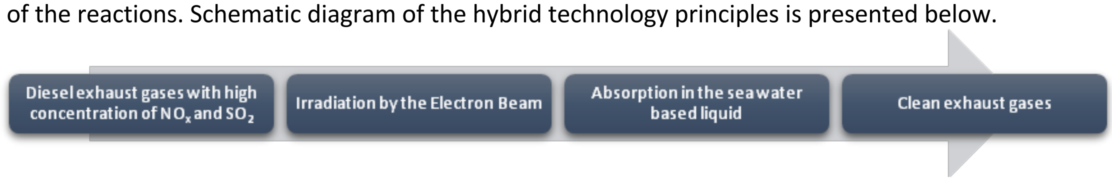
1. To conceptually proof the electron-beam accelerator application for the effective treatment of marine diesel exhaust gases.
2. To proof its technical feasibility within the simulated ship environment.
3. To demonstrate that the technology in question is capable to remove at the sufficient level SOx a NOx.
4. To provide realistic financial calculation on the cost of this technology to the ship-owner.
5. To engage and inform all relevant stakeholders during the project

To achieve these objectives the following **main tasks** are identified within this project:

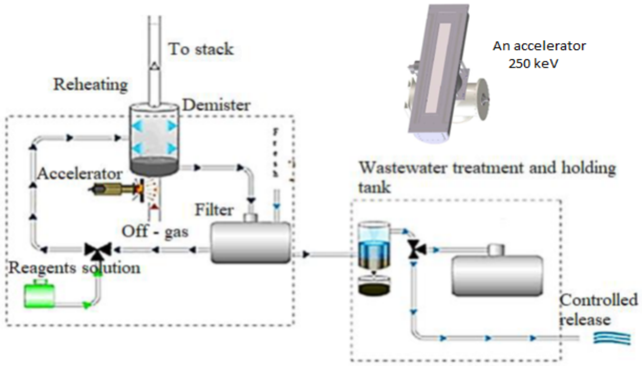
1. Effective project management, transparent coordination and targeted communication
2. Integration of the e-beam accelerator into the marine diesel engine exhaust flow system - in the simulated ship environment
3. Investigation of flue gas flow pattern and process parameter influencing on the removal efficiency of NO_x and SO_2 using computer simulation
4. Experiment measurements

Current status of the technology

A new emerging **hybrid technology** that couples the Electron Beam with the reduced size wet scrubbing methods may provide an answer to the reducing emissions from the marine shipping industry. There are two main stages involved: 1) SO2 and NOx oxidation during irradiation of wet gases by the Electron Beam from the accelerator and 2) the pollution products absorption into aqueous solution. Such a concept aims to enhance the advantages and minimize the limitations of each technology and achieve simultaneous removal of both pollutants e.g. the low removal efficiency when cleaning exhaust gases with high SO2 and NOx concentrations with only the EB and the low NOx removal efficiency with absorption, etc. The organic pollutants (VOC, PAH) may be destroyed in eb formed plasma as well. As the scrubbing solution is used salty water, easily obtainable by marine industry with the addition of the limited concentration liquid oxidant to scrub products of the reactions. Schematic diagram of the hybrid technology principles is presented below.



Technological units of the system are presented below, with the photo of an accelerator with linear cathode, which can be applied in elaborated solution. The closed loop water solution purification will be applied.
Hybrid technology is now at the level 4 in the Technology Readiness Level (there is 9 levels in this classification). This means that the technology was optimized in the laboratory level and is in the medium development phase.
The NOx removal of hybrid technology is higher than results obtained for SNCR – Selective Non Catalytic Reduction (only low concentration of NO can be treated), ozone injection, bioprocess and other plasmas methods (EB is more energy efficient than e.g. pulsed corona discharge). The SCR catalyst enables a very high removal efficiency for high NO initial concentrations, but the technology is very expensive and requires extensive amount of space. Furthermore, only NOx can be treated with this technology. The Hybrid eb method by contrast, enables a significant reduction of both pollutants in the limited reagent consumption and may assure organic pollutant destruction what may be required by new standards in the future.



Business Plan

Business development of this technology is directly dependent of this proof-of concept project – results of this project will demonstrate to the industry (ship owners, shipyards, engine manufacturers) and relevant stakeholders and decision makers, technical possibility of the electron beam accelerator application into the marine environment. Experimental results demonstrating sufficient efficiency of the SOx and NOx removal rates will be supported by the independent economic feasibility study. Very strong interest of the industry and stakeholders (including European Commission) was demonstrated in two preparatory meetings for this project (see links above and participants). To move-on maritime industry needs prof that this technology works on the marine diesel engine and is cheaper that currently available scrubber technologies. When it will be done, Consortium will be enlarged and direct funding from the industry supported by the European Community funding will be obtained. Therefore this proof-of-concept is crucial step to advance this promising accelerator technology societal application which could have enormous economic potential and very much needed solution to address the maritime environmental and air pollution problems.

One of the project partners – INCT is possessing European Patent application (see enclosed- EP17460063) related to said hybrid technology. Thus there is direct commercial interest of involved parties and Consortium members. The present value of the Patent application by INCT was evaluated by independent consulting company INVESTIN at some 540 000 EUR. The IP will be managed in the following manner, in case if the project will be approved:

- Partners IP shear of this patent will be proportional to their input to the PoC project.
- Any further IP, patents, inventions, etc - all what will be developed during the PoC and Consortium work will be equally distributed amongst Partners of Consortium
- Observers and Advisory entities are out of IP.

Work Plan and Risk Analysis

Work Package #1 (leader RTU): Project management, Coordination and Communication

Partner	Responsibility / Task	Expected outcome
RTU	1. Overall project **coordination and management**. Monitoring activities - ensuring that partners are timely following their responsibilities and verification of effective use of the received funding	2. Project kick-off meeting during ARIES annual meeting in Riga – May 2018 3. Quarterly coordination meetings via Vidyo platform 4. Mid-term review meeting during 2nd ARIES annual meeting in 2019 5. Project closing meeting in 2020
RTU	1.Coordination and Communication with relevant **stakeholders**	1. Relevant stakeholders (e.g. shipping companies, Class Societies, engine manufacturers, European Commission, EMSA, IMA, Interatnko; "Scrubbers" Group; Bimco) are directly informed about the project and its results – at least during or following the above mentioned meetings
RTU + all	1.Final project report	1. At the end of the project final report is compiled and made available to the relevant stakeholders

Work Package #2 (leader RTU): Integration of the e-beam accelerator into the marine diesel engine exhaust flow system - in the simulated ship environment. FEP is responsible for everything inside mobile unit; INCT for the scrubber and measurements; RTU for the overall design and integration of all components; RKB for dry-dock and lifting systems.

Partner	Responsibility / Task	Expected outcome
RKB	2.1. To provide with marine diesel **engine** (in-kind contribution)	1. Functioning marine diesel engine is made available at the Riga Ship yard (on dry-dock). 2. Adequate marine fuel is provided.
FEP	2.2. To provide with electron **accelerator** (in-kind contribution)	1. Mobile accelerator unit WESENITZ II and all supporting systems are made available and are delivered to RKB
RTU INCT FEP RKB Remon-towa	1. **Mechanical and electrical design** as well as technical integration concept of the mobile accelerator unit WESENITZ II 2. Design of the exhaust gas piping-system based on the operational conditions 3. Design and integration of the control and **monitoring devices**	2. Design and drawings of the mobile accelerator unit WESENITZ II is provided to RTU and RKB by FEP and INCT 3. Design of the scrubber and its elements is provided to RTU and RKB by INCT 4. Design and integration of the control and monitoring devices is provided to RTU and RKB by FEP and INCT 5. Overall design of the prototype system, including 3D model of the upper structure of the dry-dock, design of the connections between dry-dock systems and mobile accelerator unit and design of the lifting/positioning platform are designed by RTU and confirmed by the Partners 6. Monitoring devices and probes are provided by INCT
INCT	1. Design and manufacturing of the scrubber unit	1. Scrubber unit is modeled and designed based on the inputs form the FEP, RTU and RKB 2. Scrubber unit is manufactured and delivered to RKB
RKB	1. Manufacturing of the lifting/positioning platform	Platform and connection units are manufactured based on the drawings and tech specifications provided by RTU and confirmed by the Partners
RKB, RTU, FEP, INCT	1. Lifting and installation of the Mobile accelerator unit, scrubber and all systems on the dry-dock in RKB	1. Mobile accelerator unit is listed and connected to the dry-dock supply systems and exhaust duct 2. Scrubber is lifted and installed, connected to the mobile accelerator unit and dry-dock supply systems 3. All accelerator, scrubber and dry-dock systems are assembled and tested
INCT RTU RKB	1. **Installation** of the flue gas measuring devices	4. Measuring devices are provided and installed on the system
All	1. **Assembly and testing** of all the components	1. System is made ready for the tests

Work Package #3 (leader INCT): Investigation of flue gas flow pattern and process parameter influencing on the removal efficiency of NOx and SO2 using computer simulation

Partner	Responsibility / Task	Expected outcome

INCT	1. CFD (computer fluid dynamics) computer simulation will be used to model the **gas flow dynamic** inside the process vessel.	1. Process parameters, experimental - such as gas temperature, flow rate, droplet size, L/G ratio of droplet; based on modeling - process vessel dimension influence on removal efficiency of SO2 and NOx are investigated using MATLAB and KINETIC. 2. Relevant reports are provided in the form of the scientific papers

Work Package #4 (leader INCT): Experimental measurements

Partner	Responsibility / Task	Expected outcome
INCT RTU FEP CERN	1. Experimental measurements and data recording regarding continuous testing of integrated system with the diesel real off gases flow	1. Output parameters like: temperature, flow velocity and gas mixing, window conditions etc are measured and data are recorded
INCT RTU FEP	1. Analysis of the experimental results	1. Relevant analysis is made available and along with the conclusions are provided for the final project report

Work Package #5 (leader BIOPOLINEX): Economic analysis

Partner	Responsibility / Task	Expected outcome
BIOPOLINEX	1. To conduct a comprehensive business / economic / financial analysis from the point of view of the end user of the technology / installation	1. Relevant analysis and report is made available to the Consortium
BIOPOLINEX	1. To conduct a business / economic / financial analysis from the point of view of the plant manufacturer	1. Relevant analysis and report is made available to the Consortium
BIOPOLINEX	1. To assess the investment profitability based on discounted cash flows, NPV, IRR ratio as well as the payback period. 2. To calculate the break-even point for key financial parameters and to conduct the sensitivity analysis.	1. Relevant analysis and report is made available to the Consortium

Risk assessment and mitigation

The most relevant risks of the project are assessed below, followed by the proposed mitigation measures.

Project Risk Assessment Matrix - RISK FACTOR			
	LOW	**MEDIUM**	**HIGH**

Technological		- Proven state of the art - Some previous facility or site application - Some proof of application testing required	
Interference with other operations of the Partners		- Potential impact from other shipyard operations (e.g. dry-dock operations) - New interfaces must be established and managed in-situ	
Safety aspects		- shipyard is area of increased safety risks. Although there are well established they are not know to the research staff to be involved	
Visibility and Stakeholder involvement		- Major stakeholders are identified - Stakeholders neutral but interested in progress updates - Regular information sharing and communication outreach required	
Funding		- Two year duration - Detailed estimate but not yet validated - resources are not committed yet	
Time/schedule			- Compressed schedule - Activities developed only to conceptual level (some invalidated assumptions) - Resources uncommitted
Logistics and transportation		- components designed and delivered in several entities in various countries	
Quality requirements	- no specific quality requirements identified for the proof-of concept		
Number of key participants		- there are 4 key participants	
Scientific project management and participation	- Proven track record of key Partners and resources human resources immediately available		
Regulatory involvement	- At proof of concept stage no specific permits are needed, no specific certification is required		

Time/schedule risk is having HIGH probability and detrimental consequence to the project. To mitigate this following measures are envisaged:

- Compressed schedule - project manager has to engage all partners at very early stage of the project and detailed time schedule has to be developed respecting milestones and deliverables. Regular coordination meetings are foreseen.

Partners are experienced in such projects and could back-up each other easily; however this has to be properly managed. Regular information exchange is critical to identify any potential problems at very early stage. Advise of the relevant stakeholder is available.

– Activities developed only to conceptual level (some invalidated assumptions) – this mostly concerns accelerator integration in the diesel engine exhaust tract. Appropriate mathematical modeling is envisaged in the WP2 and WP3, still it will require carefully project manager oversight and peer-review which is available in the consortium.

If it will appear that some of the Partners could not deliver or will not be in position to deliver, by decision of simple majority of Consortium, after warning, this task could be (along with the relevant resources) given to another Partner or third party. This possible, since consortium is structured in the way that there is overlapping expertise and technological capabilities (e.g. two shipyards, two potential accelerator suppliers, etc).

– Resources uncommitted – this is mostly related with in-king contributions of the Partners. This will be mitigated within the Consortium agreement, where exact value and amount of this contribution will be established and agreed.

Other risks are identified as MEDIUM or LOW significance. These risks individually are not critical to the project and standing alone are not posing a threat. They are addressed in the relevant WP's and are clearly identified. However, if these risks occurring at the same time or overlapping they might became of HIGH significance. Therefore, this risks have to be made clear to all the partners and involved personnel and regularly monitored by the relevant WP leaders and project manager. Who will allocate designated staff member to follow risk assessment during the project and in case of need ad-hock meeting of the Partners could be set-up.

Milestones & Deliverables

Maximum length of this project is 2 years (however, results are expected by 31st January 2020).

Name	Description	Estimated delivery month
Deliverable 1 RTU	Project kick-off meeting is organized	M0
Deliverable 2 RKB	Functioning marine diesel engine is made available at the Riga Ship yard	M2
Milestone 1 *all*	– Design and drawings of the mobile accelerator unit WESENITZ II is provided to RTU and RKB by FEP and INCT – Design of the scrubber and its elements is provided to RTU and RKB by INCT – Design and integration of the control and monitoring devices is provided to RTU and RKB by FEP and INCT	M6-M7
Deliverable 3 RTU	Overall design of the Proof-of-concept system	M7
Deliverable 4 RKB	Lifting/positioning platform for the mobile accelerator unit and scrubber is manufactured and available at the dry-dock 3. Design and integration of the control and monitoring devices is provided to RTU and RKB by FEP and INCT 4. Overall design of the prototype system, including 3D model of the upper structure of the dry-dock, design of the connections between dry-dock systems and mobile accelerator unit and design of the lifting/positioning platform are designed by RTU and confirmed by the Partners Monitoring devices and probes are provided by INCTand all supporting systems are made available and are delivered to the Riga Ship yard	M8
Deliverable 5 FEP	Mobile accelerator unit WESENITZ II is delivered to RKB	M9

Deliverable 6 INCT	Scrubber is manufactured and delivered to RKB	M9
Deliverable 7 RTU, RKB, INCT, FEP	All parts and systems are assembled and connected to the dry-dock Measuring devices are provided and installed on the system	M9
Milestone 2 *all*	System is made ready for the tests	M10
Deliverable 8 INCT	Experimental measurements are performed and relevant conclusions compiled in the technical report	M10
Deliverable 9 INCT	Process parameters, experimental - such as gas temperature, flow rate, droplet size, L/G ratio of droplet; based on modeling - process vessel dimension influence on removal efficiency of SO2 and NOx are investigated using MATLAB and KINETIC	M11
Deliverable 10 BIOPOLINEX	Economic analysis is concluded and results are provided to the Consortium	M11
Deliverable 12 RTU	Project closing meeting is organized	M13
Deliverable 13 RTU + all	Final report is compiled and made available to the relevant stakeholders	M15

Resources (Budget)

Total budget of the Project is estimated of 546 790 EUR. This includes also in-kind contribution of the Partners – as it is indicated in the budget table below:

- Requested contribution from the ARIES Proof-of-Concept fund is 50 000 EUR
- Own contribution of the Partners (RTU in-cash) is 10 000 EUR

Project budget will be used to cover the costs arising from the aforementioned Work Packages. Detailed distribution of the estimated costs is provided in the table below:

- personal costs of the Partners
- Material/Equipment
- staff / manufacturing / equipment / travel etc. costs

All costs are indicated in EUR.

Project budget

Partner	Person-months	Personnel costs (person-months *	Material/	Total costs (personnel costs + material/equipment)	Financial contributions of the Partners	Requested contribution from the ARIES PoC

		monthly salary)	Equipment/joint test cost		Including own investments in the project - paid directly to own staff / manufacturing / equipment / travel etc. costs		
RTU	9,67	30086	4914	35000	cash	10000	25000
					in-kind		
INCT	20	45000	57790	102790	cash		10000
					in-kind	92790	
CERN	3	10000	0	10000	cash		
					in-kind	10000	
FEP	18	280000	83000	363000	cash		50000*
					in-kind	313000	
Remotowa	5	12500	0	12500	cash		0
					in-kind	12500	
RKB	5	5000	10000	15000	cash		10000
					in-kind	5000	
BIOPOLINEX	5	8500	0	8500	cash		5000
					in-kind	3500	
		391086	155704	546790			

* - A 50 000 EUR contribution from ARIES project (730871 — ARIES) to the ARIES Proof of Concept project "Development of hybrid electron accelerator system for the treatment of marine diesel exhaust gases" is provided by FEP (FRAUNHOFER GESELLSCHAFT ZUR FOERDERUNG DER ANGEWANDTEN FORSCHUNG E.V. (FEP) EV, VR4461, established in HANSASTRASSE 27C, MUNCHEN 80686, Germany, VAT number DE129515865) from its own 730871 — ARIES funding. The reporting and responsibilities on the above-mentioned funding is made by FEP on a regular basis on 730871 — ARIES reports.

ANNEX 1 – Letters of Support

Letter	Company/Institution	Signatory	Date
	Italian Coast Guard - representing Italian Flag	Admiral Nicola CARLONE	31.03.2018

Annex II

Institute of Nuclear Chemistry and Technology
Dorodna 16
03-195 Warsaw
POLAND

Report on operation of demonstrational pilot plant for hybrid treatment of flue gas from marine Diesel engine operated on ship berthed in Riga Shipyard

(within the framework of the project ARIES Proof of Concept Fund „Development of hybrid electron accelerator system for the treatment of marine diesel exhaust gases”)

By:

Dr. Andrzej Pawelec, Mr. Henryk Burliński, Dr. Andrzej Dobrowolski,
Prof. Andrzej G. Chmielewski

Warsaw, July 2019

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1. Introduction

Operation of marine diesel engines causes serious emission of sulfur and nitrogen oxides, that is a serious problem especially in harbor areas and sea routs. The problem was noticed worldwide and the regulations concerning SO_2 and NO_x emissions were introduced i.e. International Maritime Organization (IMO) ship pollution rules known as MARPOL. In the future further limitations of permissible emission are foreseen. Allowed SO_2 emission is going to be reduced to 2 g/kWh (0.4 g/kWh in Sulphur Emission Control Areas – SECAs). that corresponds with 0.5% sulphur content in fuel, while typical sulphur content in heavy fuel oil used in marine engines is about 3%. On the other hand NO_x emission standards depend on ship production date and rotation speed of engine, however in this case emission reduction at the level of 80 % is required.

Regarding Baltic Sea, international co-operation began in 1974, when HELCOM Maritime Group has been established (new Convention signed in 1992) to protect the marine environment of the Baltic Sea. Its point of interest covers all sources of pollution on land, at sea and airborne, that may influence Baltic Sea environment. This intergovernmental organization involves 10 Contracting Parties: all 9 Baltic Sea Coastal States and the European Union, while the observers are: Belarus, Ukraine, inter-governmental and nongovernmental organizations. Secretariat of HELCOM is located in Helsinki, Finland.

At Annual Meeting of the Helsinki Commission (HELCOM) held on March 10, 2016 the nine Baltic coastal countries and the EU agreed on a Roadmap which included a commitment to submit to IMO a proposal for a Baltic Sea NO_x Emission Control Area (NECA) in parallel with the North Sea. The Roadmap was submitted to the IMO MEPC 70 meeting, (October 2016) parallel with application for an ECA in the North Sea and English Channel. The applications have been accepted and during MEPC 71, the IMO adopted Resolution MEPC.286(71), amendments to MARPOL Annex VI, introducing two new NOx Emission Control Areas (ECAs). These two new NOx ECAs – the Baltic Sea and the North Sea – will be enforced for ships constructed (keel laying) on or after 1 January 2021, or existing ships which replace an engine with “non-identical” engines, or install an “additional” engine. Shipping in the Baltic Sea causes more than 13,000 tons of airborne nitrogen to be emitted each year, worsening the existing problem of eutrophication. After the Baltic Sea was declared a NOx ECA, it is expected to reduce nitrogen pollution by around 7,000 tons annually.

There are several solutions of this problem as fuel desulfurization or sea water scrubbing in the case of SO_2 and fuel combustion process modification (engine modification) or selective catalytic reduction (SCR) process application in the case of NO_x. All of these processes has its limitations. Low sulphur fuel is much more expensive and may be harmful for older engines. Similarly, fuel combustion process modification has limited NO_x emission reduction potential. Therefore the most popular solution for marine industry is combination of sea water scrubbing combined with selective catalytic reduction. However these are two separate processes realized in two separate devices, that is problematic due to limited space on ship board. In this case one process allowing for simultaneous removal of both pollutants may be an alternative.

The response may be electron beam flue gas treatment (EBFGT) technology. The technology was already applied in the power industry and further research on its development is carried on. Institute of Nuclear Chemistry and Technology is one of the best known scientific centers in the world working on different applications of this technology. During the research carried on in the Institute, the process was adopted to marine Diesel off gases treatment conditions. In this solution called hybrid EBFGT process, two main processes are combined. In the first step flue gasses are irradiated for oxidation of NO and SO_2 to higher oxides to allow remove both SO_x and NO_x in the process of wet scrubbing with high efficiency. On the base of theoretical and laboratory works a background of the process was elaborated. Next step was examination of the process in real conditions in pilot scale.

This task was realized in the frame of the project “PoC Development of hybrid electron accelerator system for the treatment of marine diesel exhaust gases”. The main goal of this project was to demonstrate hybrid electron beam flue gas treatment technology for efficient removal of SO_2 and NO_x from marine Diesel engine flue gases. The project was realized in Riga Shipyard (Latvia) in international cooperation between Riga Technical University (Latvia), Institute of Nuclear Chemistry and Technology (Poland) and Fraunhofer FEP (Germany). CERN, the European Organization for Nuclear Research, based in Geneva (Switzerland), provided support and consultancy.

The report provides the results of the operation of pilot hybrid electron beam marine flue gases treatment facility, that may be a starting point for further development of the technology. Due to the period of preparation of the set at Riga Shipyard and limited access time to the emitter (ship) and accelerator, possibility of only two days field tests was granted. Therefore the tests main objective was demonstration of possible integration of accelerator with ship engine, gas spray cooler and wet scrubber at real practical conditions, what was never demonstrated before.

2. Main principles of the tested technology

In the e-beam technology, electrons are accelerated by a high voltage in a vacuum region before being injected through thin foil windows to the flue gases at the atmospheric-pressure processing chamber (plasma reactor). The energetic electrons collide with exhaust gas molecules and produce reactive free radicals, atoms, ions and secondary electrons that decompose the pollutants molecules in the irradiated flue gases. During this process, pollutants such as SO_2 and NOx are oxidized to higher oxides which then react with the water vapour present in the flue gases, resulting in the formation of H_2SO_4 and HNO_3.

$NO + O(^3P) + M \rightarrow NO_2 + M$ (M is a third inert body in the reaction system)

$O(^3P) + O_2 + M \rightarrow O_3 + M$

$NO + O_3 + M \rightarrow NO_2 + O_2 + M$

$NO + HO_2\cdot + M \rightarrow NO_2 + {*OH} + M$

$SO_2 + \cdot OH + M \rightarrow {*HSO_3} + M$

${*HSO_3} + O_2 \rightarrow SO_3 + {*HO_2}$

$NO_2 + {*OH} + M \rightarrow HNO_3 + M$

$SO_3 + H_2O \rightarrow H_2SO_4$

In the case the SO_2 inlet concentration is high, the removal efficiency of NO increases noticeably, especially at a higher irradiation doses range. effect of the presence of SO_2 in enhancing NO_x removal efficiency can be explained by the chain of reactions, Radicals $HO_2^{\bullet}$, which are produced during reactions with SO_2, react with NO and oxidize them into NO_2. This is later converted to HNO_3. When the NO inlet concentration is high, this synergistic effect is more advantageous at high concentrations of SO_2

The general scheme of the electron beam interaction with the flue gas is given in the Figure 1.

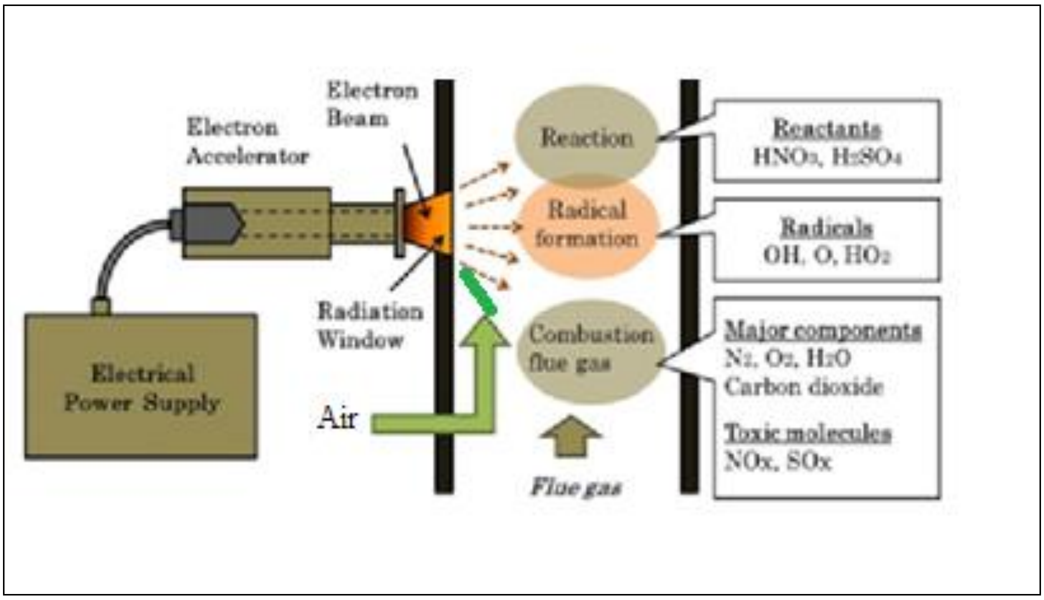


Figure 1. Scheme of the electron beam interaction with the molecules of the flue gas components.

For diesel off gases treatment, where NO_x concentration is high, electron beam technology was coupled with the wet scrubbing method. The purpose of the hybrid technology is to enhance the removal efficiency of NO_x and SO_2.

The recent developments consider application of the solution where absorption of gas reactions products is achieved in a spray of droplets introduced in the irradiation zone. The main reactions causing NO_x removal are:

$*OH + NO \rightarrow HNO_2$

$*OH + NO_2 \rightarrow HNO_3$

and process is hindered by main back reactions:

$NO + O \rightarrow NO_2$

$NO_2 + O \rightarrow NO_3$

$O + NO_2 \rightarrow O_2 + NO$

$O + NO_3 \rightarrow O_2 + NO_2$

Therefore to shift reaction equilibrium into product side, the removal of the products of the first reactions is necessary. These is possible when the products are removed from the gaseous phase to liquid or solid phase as it was in the case of earlier developed technology to be used in fossil fuel fired boilers where formed acids reacted with ammonia to form solid products. The principle of the idea is illustrated at the Figure 2. There are two main stages involved: 1) SO_2 and NO_x oxidation during irradiation by the Electron Beam from the accelerator and 2) the pollution absorption into aqueous solution via Wet Scrubbing. Such a concept aims to enhance the advantages and minimise the limitations of each technology and achieve simultaneous removal of both pollutants e.g. the low removal efficiency when cleaning exhaust gases with high SO_2 and NO_x concentrations with only the EB and the low NO_x removal efficiency with absorption, etc.

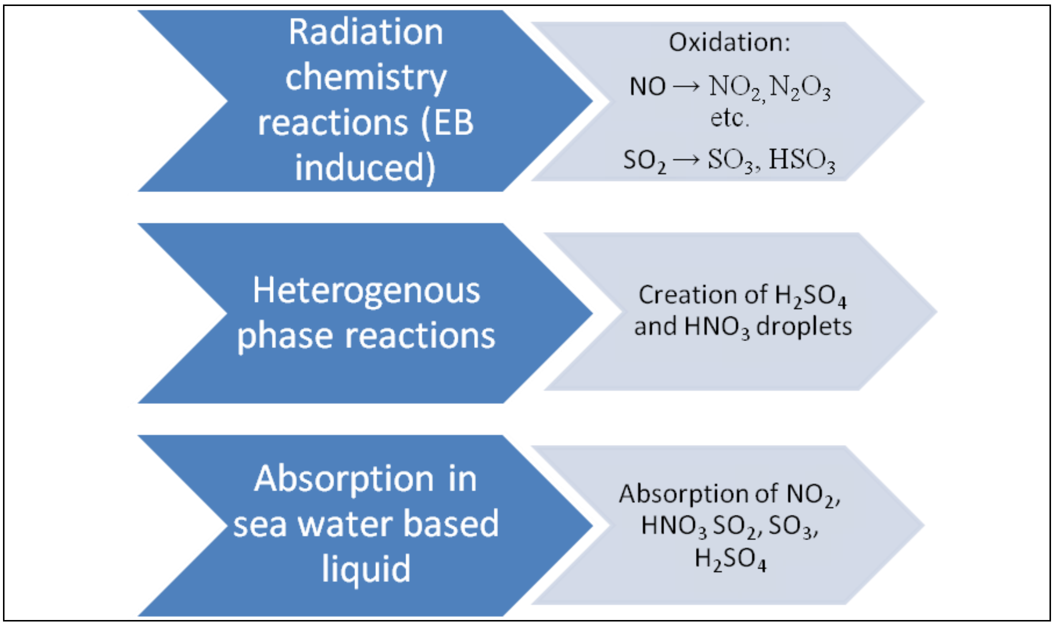


Figure 2. Scheme of the hybrid process based on Electron Beam and Wet Scrubbing with droplet spray applied.

Application of self shielded accelerators of energy ca 300 kV is considered and two side irradiation has to be applied, due to uniform dose distribution requirements (Figure 3).

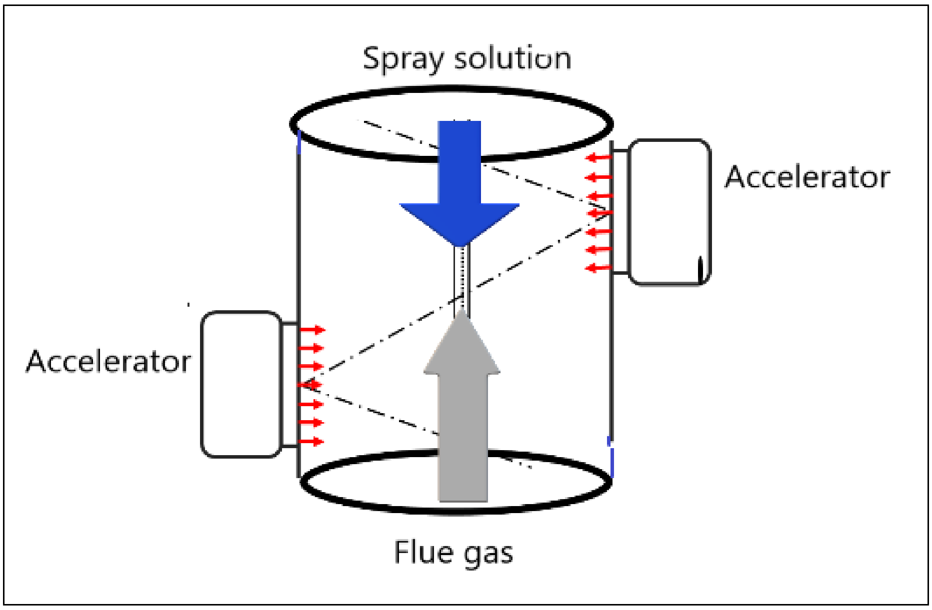


Figure 3. Conceptual process vessel for diesel off gases treatment. Two sides irradiation with applications of self-shielded accelerators.

2.1. Post eb treatment scrubber for products absorption

Another important factor influencing process is post irradiation scrubber removal efficiency dependence on mass transfer, therefore high efficiency absorber should be applied as the second stage of installation. Gas and vapor collection in wet scrubber air pollution control devices is achieved by adsorption. The process of absorption refers to the contacting of mixture of gases with a liquid so that part of one or more of the constituents of the gas will dissolve in the liquid. The necessary condition for absorption is the solubility of pollutants in the absorbing liquid. The rate of mass transfer of the soluble constituents from the gas to the liquid phase is determined by diffusional processes occurring in each side of the gas-liquid interface. Equilibrium is another important factor to be considered in controlling the operation of absorption systems. The rate at which pollutant will diffuse into an absorbent liquid will depend upon the departure from equilibrium that is maintained. The rate at which the pollutant mass is transferred from one phase to another depends on a so-called mass transfer or rate coefficient, which equates the quantity of mass being transferred with the driving force. As can be expected, this transfer process ceases upon the attainment of equilibrium.

The scrubbing system is composed of exhaust hoods and ducts handling airborne contaminants. Gas pretreatment equipment may be required for coarse particulate removal and for cooling before the contaminants enter the scrubber vessel. The contaminant-laden droplets are removed by the entrainment separators. The clean gas is then passed through an induced-draft fan and up the stack. Forced-draft fans upstream of the scrubber are also used.

From among the generally accepted methods of considering the mass exchange process, it was decided to quantify the mass exchange process, including absorption efficiency. This value in a very simple and transparent way allows to assess the impact of basic process parameters on the effectiveness of gas treatment. It has been assumed that the absorption efficiency is a function of the following variables:

$\eta=f(U_e,L/G,H,C_o,C_r)$, where

η - absorption efficiency [%],

U_e - gas velocity calculated on the empty column cross-section [m/s],

L/G - spraying density of the absorption solution, liters of solution per cubic meter of gas [L/m^3],

H – column packing height [m],

C_o - initial concentration of NO_x (calculated as NO_2) in the gas, [mg/m^3] or [vol %],

C_r - concentration of the absorption solution, [kg/m^3] or [mass%].

Flow regime influence mass transfer coefficient and specific area related to column packing type affects mass transfer flux. These parameters beside process chemistry define overall efficiency of applied solution.

The key operating parameters affecting the pollution collection are:

- ✓ Liquid-to-gas ratio
- ✓ Pressure drop
- ✓ Velocity/gas flow rate
- ✓ Temperature
- ✓ Particle size distribution (particulate)

Typical L/G ratios for wet scrubbers are presented in Table 1.

Table 1. Typical L/G ratios for wet scrubbers.

Scrubber Type	**L/G ratio [dm^3/m^3]**
Venturi	0,80 – 1,25
Cyclonic spray tower	0,80 – 1,60
Spray tower	1,60 – 3,21
Impingement plate	0,48 – 0,80
Packed bed	0,16 – 0,64

The liquid-to-gas flow rate (L/G) is a calculated value, reflecting the liquid recycling rate for every volume of gas cleaned. High L/G ration are used for high-temperature gas streams and high-grain loadings. Should the L/G ratio fall below the design value, collection efficiency will diminish. High L/G ratios are required for high-temperature gas streams to prevent pollutant reentrainment. When the L/G ratio is not sufficient to saturate the gas stream, pollutant laden droplets reentering the scrubber from recycled liquors will evaporate (evaporative cooling) and leave the previously captured particulate reentrained in the gas stream. Should this occur, pretreatment with clean liquor (for quenching) may be required. The quenching stage saturates the gas stream to minimize evaporation in the scrubbing stage.

The pressure drop across a scrubber includes the energy loss across the liquid gas contacting section and entrainment separator, with the former accounting for most of the pressure lost. A low pressure drop scrubber ranges from 0,05 to 0,25 m H_2O, medium from 0,25 to 0,76 m H_2O and high, 0,76 m and above. The higher the pressure drop, the greater the particulate collection efficiency for both particle size and concentration. Typical pressure drops for various types of wet scrubbers are presented in Table 2.

Table 2. Typical scrubber pressure drops.

Scrubber Type	Pressure Drop [m H_2O]
Venturi	0,25 – 1,78
Centrifugal (cyclonic) spray	0,02 – 0,08
Spray tower	0,02 – 0,05
Impingement plate	0,02 – 0,25
Packed bed	0,02 – 0,25
Wet fan	0,10 – 0,25
Self-induced spray (orifice)	0,05 – 0,51

The collection of most scrubbers depends upon the velocity of the gas stream through the liquid-contacting section of the scrubber vessel. For particulates, the relative velocity between washing liquids (droplets) and particulates is critical to contaminant collection. In the case of high-energy venturi scrubbers, a velocity of 200 m/s can be delivered. Fine droplet size and high density lead to increased removal efficiency.

When a high-temperature gas stream exhaust enters the scrubber, the volumetric flow rate diminishes accordingly (based on the temperature of the scrubber liquid) because the gas is being cooled by the scrubber liquors. When the system flow rate decreases, the resulting relative velocity may not be sufficient to collect the desired amount of particulate and emissions will increase. For a packed tower or tray tower, low or no gas flow might indicate plugged packing in the absorber, fan problems, duct leaks or an increase in liquid flow to the tower. Increased gas flow might indicate a low liquid flow rate, packing failure or a sudden opening of a system damper.

Wet scrubber inlet and outlet temperatures are also key parameters that should be monitored when controlling gas streams with elevated temperatures. An increase in temperature could indicate a failure of the cooling equipment, which would result in decreased pollutant collection efficiency and perhaps damage to the scrubber.

Performance of a scrubber controlling particulate emissions depends on the gas stream particulate size distribution. Efficient collection of submicron contaminants challenges the application of any type of control system. High-energy venturi scrubbers are designed for submicron contaminant collection. Changes in process equipment or operation can change the particle size distribution and , in turn, impact collection efficiency.

SO_2 absorption at an industrial scale in maritime sector is most commonly practiced in packed or spray towers, which are often combined with venturi nozzle. In the spray tower, the liquid is sprayed into a gas stream by means of a nozzle which disperses the liquid into a fine spray drops. The flow may be countercurrent, as in vertical towers with the liquid sprayed downward, or parallel, as in horizontal spray chambers. These devices have the advantage of low pressure drop for the gas but also have a number of disadvantages. There is a relatively high pumping cost for the liquid, owing to the pressure drop through the spray nozzle. The tendency for entrainment of liquid by the gas leaving is considerable, and mist eliminators will almost always be necessary. Unless the diameter/length ratio is very small, the gas will be fairly thoroughly mixed by the spray and full advantage of countercurrent flow cannot be taken. Ordinarily, however, the diameter/length ratio cannot be made very small since then the spray would quickly reach the walls of the tower and become ineffective as a spray.

A packed tower is essentially a piece of pipe set on its end and filled with inert material or "tower packing." Liquid poured into the top of the tower trickles down through the packing, gas pumped into the bottom of the tower flows counter currently upward. The intimate contact between gas and liquid achieved in this way effects the gas abortion. Analyzing a packed tower involves both mass transfer and fluid mechanics. The mass transfer, detailed in the following section, determines the height of the packed tower. This mass transfer is described as molar flows, partly because of the chemical reactions that often occur. The fluid mechanic determines the cross-sectional area of the packed tower. The fluid mechanics is described as mass flows, a consequence of the physics that control the process.

The fluid mechanics in the packed tower is dominated by the inert material in the packed tower. This material can be small pieces dumped randomly or larger structures carefully stacked inside the tower. Random packing is cheaper and more common whereas structured packing is more expensive but more efficient.

Generally random packings offer larger specific surface area (and larger gas pressure drop) in the smaller sizes, but they cost less per unit volume in the larger sizes. As a rough guide, packing sizes of 25 mm or larger are ordinarily used for gas rates of 0,25 m^3/s, 50 mm or larger for gas rates of 1 m^3/s. During installation the packings are poured into the tower to fall random and in order to prevent breakage of ceramic or carbon packings, the tower may first be filled with water to reduce the velocity of fall.

While using packed gas absorption tower another crucial issue is an adequate initial distribution of the liquid at the top of the packing. As dry packing is completely ineffective for mass transfer, various devices are used for liquid distribution. Spray nozzles generally result in too much entrainment of liquid in the gas to be useful. In small tower it is possible to use a ring of perforated pipe. For larger diameters, distributor many other arrangements are available. It is generally considered necessary to provide at least five point of introduction of liquid for each 0,1 m^2 of tower cross section for large tower (d ≥ 1,2 m) and a greater number for smaller diameters. In the case of random packings, the packing density, i.e., the number of packing pieces per unit volume, ordinarily less in the immediate vicinity of the tower walls and this leads to a tendency of the liquid to segregate toward the walls and the gas to flow in the center of the tower (channeling). This tendency is much less pronounced when the diameter of the individual packing pieces is smaller thanat least one-eighth the tower diameter, but it is recommended that, if possible, the ratio 1:15. Even so it is customary to provide for redistribution of the liquid at intervals varying from 3 to 10 times the tower diameter, but at least every 6 or 7 m. Knitted mesh packings placed under a packing support make good redistributors.

Another important parameter to go over is to use liquid flows that are high enough to avoid channeling and achieve loading. It is also expected to use gas flows that are low enough to avoid flooding.

3. Layout of facility constructed at Riga Shipyard.

There were not technical and operational possibilities to apply solutions required for designed novel hybrid system testing covering all its components. No spray was introduced to the irradiation zone (due to the fact that existing FEP accelerator for grain irradiation had to be used) and only one side irradiation has been applied (only one side installed accelerator was operational during the tests). The two stage installation was tested; diesel engine – inlet pipe – accelerator irradiation zone – inter stages pipe – packed absorption column – outlet pipe.

Pilot hybrid electron beam marine flue gas treatment facility located in Riga Shipyard consisted of the following units:

- flue gas ship diesel (provided by RTU),
- electron beam unit (provided by FEP),
- seawater scrubbing unit (provided by INCT),
- scrubbing solution closed loop system (provided by INCT),
- measurement points ports and monitoring system (provided by INCT).

The general scheme of the pilot plant is presented in Figure 4.

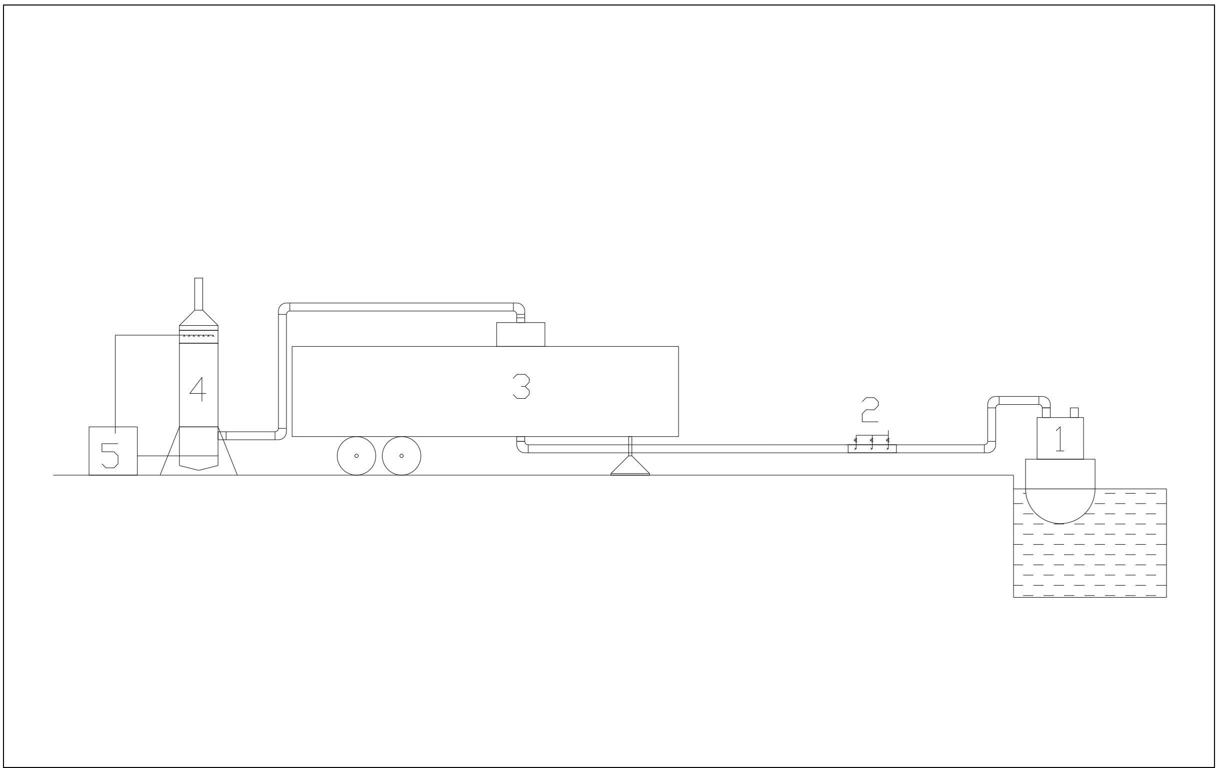


Figure 4. General scheme of pilot hybrid electron beam flue gas treatment plant.
1 – flue gas source, 2 - spray cooler, 3 - mobile accelerator, 4 – scrubber, 5 – seawater tank

A tugboat "Orkans" berthed at the bank of the shipyard was used as the source of flue gas. This small ship is equipped in two two-stroke Diesel engines of Russian production. Outlet of gas pipe of one of the engines was connected to accelerator by 320 mm pipe. Between gas source and accelerator a spray cooler was installed, to protect accelerator window against too high gas temperature. However air curtain gave a good protection of this foil.

A mobile accelerator of Fraunhofer FEP manufacturing (WESENITZ-II EB Seed Dressing Container) was used as an irradiation device. The device was originally designed for seed irradiation and was adopted to flue gas irradiation for this project purposes. Irradiation chamber is of rectangular cross section (120 x 1560 mm) and 1180 mm height. Gas flows vertically from bottom to top direction and is irradiated from both sides by use of two 125 kV accelerators. Maximal current for one accelerator is 100 mA. The single window with air curtain accelerators were applied in the device.

Unfortunately during the experiments one of the accelerators was out of order. Two pipe connectors (320 mm at the bottom and 250 mm at the top) were installed in order to connect gas pipes. Gas between accelerator and scrubber was transported by 250 mm pipes (Figure 5).

Figure 5. View of trailer hosting FEP accelerator and scrubber connected to the eb system.

A counter current gas – liquid flow packed scrubber was selected as absorber for purpose of this project. The device of 1.2 m diameter and 5.5 m height was filled with Bialecki rings. Filling height was 2.6 m. A closed loop system was selected for water circulation in the scrubber. The circulating water was stored in two tanks filled with 3 m^3 of seawater. The water from the tanks was filtered and pumped to a system of nozzles located at the top of the scrubber and sprayed at the top of the filling, then flowed to the bottom of the device and back to the tanks by gravity. The gas from the irradiation unit was directed to the lower part of the scrubber and was released to the atmosphere by a stack located at the top of the device.

Bialecki rings were used as a packing (Figure 6).

Figure 6. Bialecki rings.

Basis of the scrubber design were calculations based on below presented scheme. Parameters notation:

ρ_g – flue gas density at temperature at the scrubber inlet,

η_g – flue gas viscosity at temperature at the scrubber inlet,

D_g – diffusion coefficient of NO_2 in gas phase (1,54 * 10^{-5} m^2/s),

d – scrubber diameter (1,2 m),

d_{wp} – Bialecki's ring diameter (0,035 m),

P – pressure at scrubber (10^5 Pa),

a – specific packing area (157,3 m^2/m^3),

H – scrubber height (2,6 m).

Considered that main mass transfer resistance is on gas phase side.

Volumetric gas flow at experiment conditions:

$$Q_{spalin} = Q_{Nm3/h} * \frac{t + 273}{273}$$

Mass gas flow:

$$Q_{sp\ (mas)} = \frac{Q_{spalin} * \rho_g * 4}{3600 * d^2 * \Pi} \left[\frac{kg}{m^2 * s}\right]$$

Mass transfer coefficient correlation equation:

$$Sh_g = 0{,}11 * Re_g^{0{,}8} * Sc_g^{0{,}33}$$

$$Re_g = \frac{Q_{sp\ (mas)}}{a * \eta_g}$$

$$Sc_g = \frac{\eta_g}{\rho_g * D_g}$$

Mass transfer coefficient β_{gc} based on Sh_g

$$\beta_{gc} = \frac{Sh_g * D_g}{d_{wp}} \left[\frac{m}{s}\right]$$

$$\beta_{gy} = \beta_{gc} * \frac{P}{RT} * M[NO_2] \left[\frac{kg}{m^2 * s}\right]$$

$$HTU = \frac{Q_{sp\ (mas)}}{\beta_{gy} * a} [m]$$

$$NTU = \frac{H}{HTU}$$

Scheme of the scrubber is given in Figure 7.

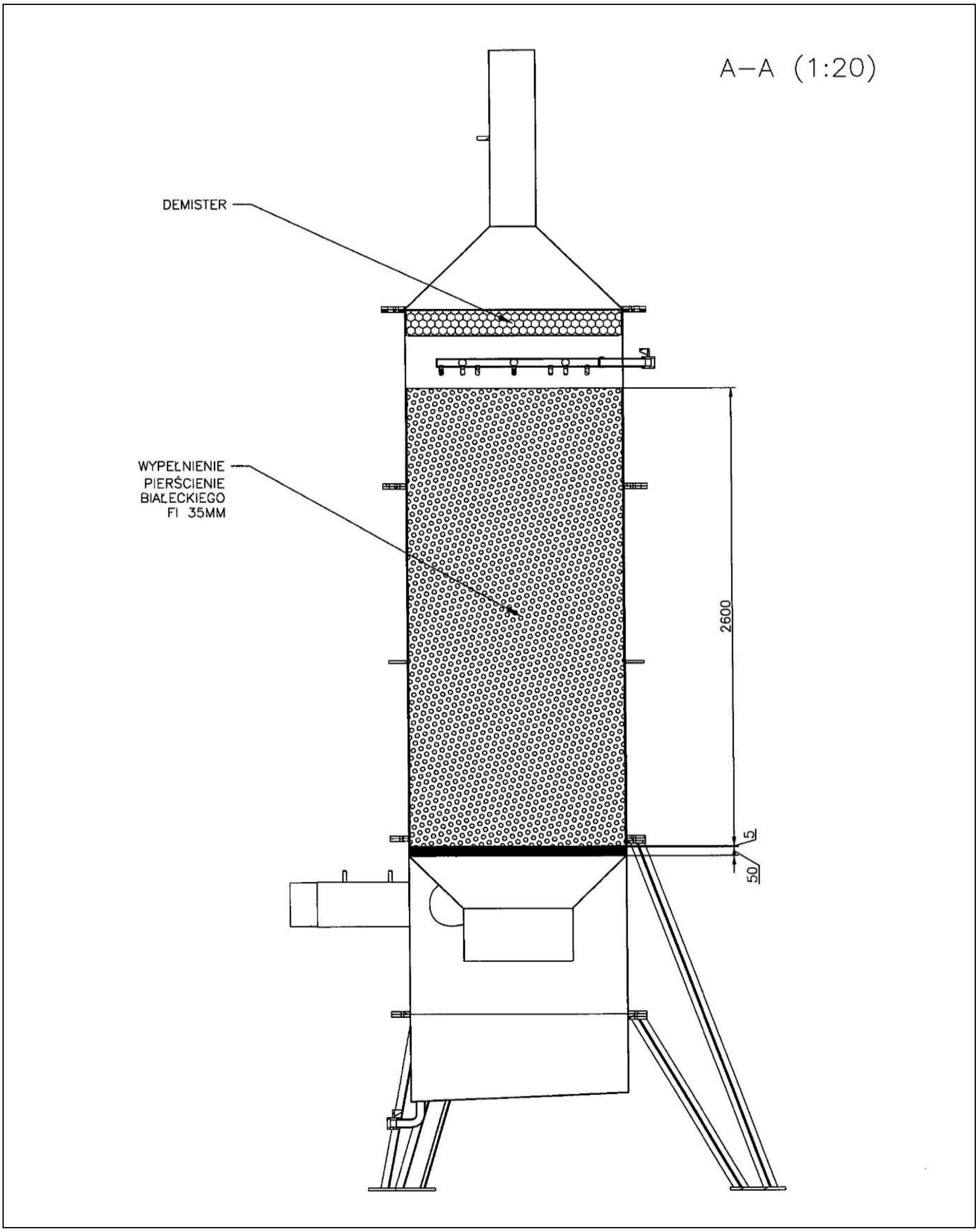


Figure 7. Scheme of packed wet scrubber.

The gas sampling points were located up stream of the accelerator, upstream of the scrubber and at the gas outlet stack. In this way gas parameters were measured at the inlet of the installation, after irradiation and after treatment at the outlet of the plant. Moreover five temperature measurement points (down stream of engine, upstream spray cooler, irradiation unit gas inlet, scrubber inlet and scrubber gas outlet) and one for gas velocity measurement point (before irradiation) were located. The scheme of measurement points is presented in Figure 8.

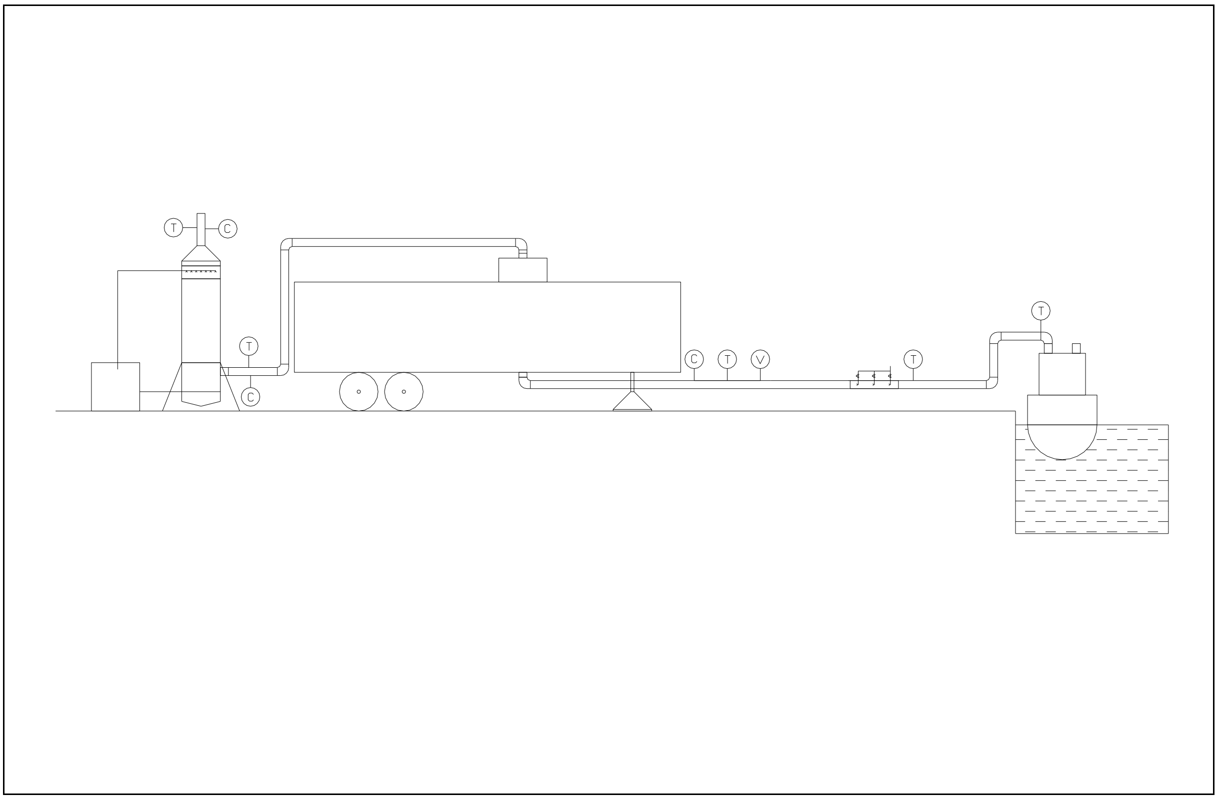


Figure 8. Scheme of the measurement points in pilot plant for marine flue gases treatment by hybrid electron beam method.

The temperature of flue gas was measured in five main points (see *Figure 8)* by means of thermocouples type K manufactured by Czaki (Poland). Flue gas velocity was measured by Testo 452 anemometer produced by Testo, Germany. Flue gas velocity and temperature at the inlet to irradiation unit was used for determination of flue gas flow rate.

Flue gas composition was determined in three main points of facility: at the inlet to the irradiation unit, after irradiation and after treatment at the outlet of the plant. Two different types of analyzers were used: Kane Quintox flue gas analyzer (Kane Int. Limited, UK) at the inlet and outlet of the treatment plant and Land Lancom series II portable gas analyzer manufactured by AMETEK Land, United Kingdom after irradiation unit. Concentration of the following elements of gas composition were determined: sulfur dioxide (SO_2), nitrogen monoxide (NO), nitrogen dioxide (NO_2), oxygen (O_2), carbon dioxide (CO_2), carbon monoxide (CO), and hydrocarbons (C_xH_y).

4. Methodology

The following parameters of flue gas were measured: flue gas velocity, flue gas temperature and flue gas composition.

The whole amount of flue gas generated by marine Diesel engine was treated in the system. The experiments were realized for three engine loads (0% - idling run, 50% and 100%). After engine ignition the scrubber pump was switched on and required water flow rate was set by an inverter. Water flow rate was measured by a rotameter. In the same time the accelerator was started and after stabilizing of gas flow rate the gas parameters were recorded.

Water tanks were filled up with Baltic Sea water before the series of experiments and solution was not changed during the whole cycle of experiments. Therefore close loop system was tested. In order to keep water ability for acidic gases absorption it's pH was kept over 7.5 by addition of sodium hydroxide. pH of the scrubber circulating water was controlled by pH 3210 Set 2 pH-meter manufactured by WTW (Germany). For enhance of the oxidation potential and improvement of NO_x removal efficiency an oxidant ($NaClO_2$) was also added to the water. Total amount of oxidant was 10 kg. First set of experiments was realized without oxidant (series 1), then 3 kg of this salt was added to the water (series 2). Series 3 of experiments was realized after addition of 7 kg of oxidant more.

The results of the measurements were recalculated to give the required dependences. The gas flow rate was calculated from gas velocity and pipe diameter:

$Q = 3600 * V * 3.14*d^2/4$, where:

Q – gas flow rate [m^3/h],
V – gas velocity [m/s],
d – pipe diameter [m] (0.32m).

The absorbed dose was calculated according to the formula:

$D = 3.6 * A * U*I/m$, where:

D – absorbed dose [kGy],
A – dose coefficient (0.6),
U – accelerator voltage [kV],

I – accelerator current [mA],

m – gas mass flow rate [kg/h].

During the accelerator operation a stream of air was blown on the reaction chamber window in order to protect them This air was mixed with treated gas making it's dilution and lowering the concentrations of measured pollutants. Therefore, for proper evaluation of pollutants removal efficiency the outlet concentration of pollutants was corrected as for no dilution state. This correction was made according to the formula:

$C_{cor} = C * (21 - O_{in})/(21 – O_{out})$, where

C_{cor} – corrected pollutant concentration [ppm],

C - measured pollutant concentration [ppm],

O_{in} – oxygen concentration at the inlet [%],

O_{out} – oxygen concentration at the outlet [%].

Removal efficiency was calculated as follows:

$E = 100 * (C_{in} – C_{out})/C_{in,}$, where:

E – removal efficiency [%],

C_{in} – inlet pollutant concentration,

C_{out} – corrected outlet pollutant concentration.

During whole set of experiments only one of the accelerators was operational, therefore one side gas irradiation was applied. This do not assure equal dose distribution over gas stream intersection. For calculation mean dose for whole gas elements was considered. In the fact the higher dose was absorbed in stream close to accelerator window and lower at the other side of gas stream. The dose distribution can be evaluated on the basis of irradiation chamber geometry and electron beam energy and current to be provided by FEP. The whole system was available for testing for two days only.

5. Results and discussion

The experiments were carried on 4th and 5th of July 2019. The measured parameters are presented in Table 4. As desulfurized fuel was provided no SO_2 was present in the flue gas, what was other drawback of testing program. Therefore this pollutant is not listed in the table. Analogically for better understanding of the dependences only two of 5 measured gas temperatures were shown. Some data in experiment 4 are missing due to analyzer malfunction.

Removal efficiencies of the pollutants were calculated according to previously presented formulas and the elaborated data are presented in Table 5.

Plasma and oxidant oxides NO to NO_2 increasing amount of nitrogen dioxide to be absorbed in the solution. During the experiments higher concentrations of NO_2 at the outlet of facility were observed, this pollutant should be fully absorbed in well operated scrubber, what should be considered during on board testing. Solubility of NO in water is equal to ca. 0.032 g/l and NO_2 213 g/l, therefore application of modern scrubber shall remove at least 95% of NO_2. According to these facts theoretical removal rate of NO_x was calculated assuming actual NO and 95% NO_x removal. The results are presented in Table 5.

Table 3. Scrubber parameters

Experiment code			1	2	3	4	5	6	7	8	11	12	13	14	15	16	17
Engine load		%	0	50											100		
Oxidant added		kg	0				3				10						
Gas flow rate		Nm^3/h	-	4763,9	4831,2	4771,8	4703,0	4807,1	4942,7	4751,7	4915,2	4950,0	4917,8	4927,6	4605,5	4494,6	4804,1
Gas temperature	Engine outlet	°C	-	140	146	147	147	156	151	159	152	155	156	157	229	237	226
	Scrubber inlet	°C	-	76	97	98	81	96	90	108	80	90	95	90	97	100	96
Accelerator	Beam voltage	kV	-	125	125	125	125	125	125	125	125	125	125	125	125	125	125
	Beam current	mA	-	75	75	100	50	75	100	100	100	75	50	100	50	0	100
Scrubber	Water flow rate	m^3/h	-	10	10	10	10	10	10	20	10	10	10	20	10	10	10
	Water pH	-	-	8,6	8,3	8,3	8,3	8,3	7,4	7,4	9,1	8,7	8,3	7,9	7,9	7,9	7,8
Inlet gas composition	CO_2	%	-	2,4	2,4	2,4	2,5	2,5	2,5	2,5	2,0	2,6	2,6	2,5	4,2	4,3	4,1
	O_2	%	-	18,1	18,2	18,1	17,0	17,9	17,9	17,9	17,4	17,9	17,9	17,8	15,6	15,6	15,8
	NO	ppm	-	209	211	212	216	228	233	252	298	237	244	239	667	673	615
	NO_2	ppm	-	20	18	18	19	20	22	19	19	17	18	21	25	27	28
	NO_x	ppm	-	229	229	230	235	248	255	271	317	254	262	260	692	700	643
	HC	ppm	-	13	22	25	13	0	0	1	0	0	1	0	0	0	5
Scrubber parameters	HTU	m	-	0,834	0,879	0,878	0,838	0,874	0,871	0,902	0,842	0,868	0,878	0,869	0,869	0,874	0,874
	NTU	-	-	3,117	2,958	2,961	3,103	2,975	2,985	2,882	3,088	2,995	2,961	2,992	2,992	2,975	2,975
	H	m	2,6	2,6	2,6	2,6	2,6	2,6	2,6	2,6	2,6	2,6	2,6	2,6	2,6	2,6	2,6

Table 4. The parameters measured during the experiments on pilot plant for hybrid electron beam treatment for flue gases from marine Diesel engines.

Experiment code			1	2	3	4	5	6	7	8	11	12	13	14	15	16	17
Engine load		%	0	50											100		
Oxidant added		kg	0				3				10						
Gas velocity		m/s	13,6	24,0	24,4	24,1	22,8	24,4	24,4	24,6	24,7	25,0	24,9	24,7	26,0	26,0	27,0
Gas temperature	Engine outlet	°C	70	140	146	147	147	156	151	159	152	155	156	157	229	237	226
	Accelerator inlet	°C	51	125	126	126	110	128	117	136	124	126	127	123	173	184	171
Accelerator	Beam voltage	kV	125	125	125	125	125	125	125	125	125	125	125	125	125	125	125
	Beam current	mA	50	75	75	100	50	75	100	100	100	75	50	100	50	0	100
Scrubber	Water flow rate	m^3/h	10	10	10	10	10	10	10	20	10	10	10	20	10	10	10
	Water pH	-	10,1	8,6	8,3	8,3	8,3	8,3	7,4	7,4	9,1	8,7	8,3	7,9	7,9	7,9	7,8
Inlet gas composition	CO_2	%	1,4	2,4	2,4	2,4	2,5	2,5	2,5	2,5	2,0	2,6	2,6	2,5	4,2	4,3	4,1
	O_2	%	19,1	18,1	18,2	18,1	17,0	17,9	17,9	17,9	17,4	17,9	17,9	17,8	15,6	15,6	15,8
	NO	ppm	95	209	211	212	216	228	233	252	298	237	244	239	667	673	615
	NO_2	ppm	15	20	18	18	19	20	22	19	19	17	18	21	25	27	28
	NO_x	ppm	110	229	229	230	235	248	255	271	317	254	262	260	692	700	643
	HC	ppm	0	13	22	25	13	0	0	1	0	0	1	0	0	0	5
Outlet gas composition	CO_2	%	1	1,9	2	1,9	2	2,1	2,1	2,2	2,2	2,1	2,2	2,1	2,7	2,8	2,7
	O_2	%	19,9	18,7	18,8	18,7	18,7	18,6	18,5	18,4	18,2	18,4	18,5	18,5	17,7	17,6	17,8
	NO	ppm	10	85	101	70	103	96	85	90	79	77	0	0	230	312	84
	NO_2	ppm	29	41	34	48	31	41	44	51	52	52	119	113	67	47	132
	NO_x	ppm	39	126	135	118	134	137	129	141	131	129	119	113	297	359	216
	HC	ppm	0	16	0	11	13	3	0	12	13	0	7	0	0	0	2

Table 5. Removal efficiencies of the pollutants obtained during the experiments on pilot plant for hybrid electron beam treatment for flue gases from marine Diesel engines.

Experiment code			1	2	3	4	5	6	7	8	11	12	13	14	15	16	17
Engine load		%	0	50											100		
Oxidant concentration		mg/l	0				1				3,3						
Gas flow rate		Nm^3/h	3316,1	4763,9	4831,2	4771,8	4703,0	4807,1	4942,7	4751,7	4915,2	4950,0	4917,8	4927,6	4605,5	4494,6	4804,1
Gas temp. at accelerator inlet		°C	51	125	126	126	110	128	117	136	124	126	127	123	173	184	171
Dose		kGy	4,1	4,2	4,2	5,7	2,9	4,2	5,5	5,7	5,5	4,1	2,7	5,5	2,9	0,0	5,6
Inlet concentration	NO	ppm	95	209	211	212	216	228	233	252	298	237	244	239	667	673	615
	NO_x	ppm	110	229	229	230	235	248	255	271	317	254	262	260	692	700	643
Removal rate	NO	%	81,8	48,2	39,1	58,2	39,2	46,3	55,3	57,4	65,2	60,4	100,0	100,0	43,2	26,5	77,6
	NO_x	%	38,8	30,0	25,0	35,1	27,3	29,6	38,1	38,0	45,8	38,1	44,2	44,4	29,2	18,7	45,0
Calculated removal rate if high efficiency scrubber applied *	NO_x	%	83,6	52,3	43,5	61,1	43,7	50,2	58,8	60,1	67,0	62,7	99,7	99,6	45,0	29,1	78,4

*Removal possible after application of high efficiency scrubber providing 95% removal of NO_2.

Gas composition is the background for the processes undergoing during gas irradiation and absorption efficiency. During the experiments very high oxygen concentration was noticed regardless the sampling point and used analyzer. It may be also noticed, that apart of idling run, flue gas flow rate is at the same level. Moreover there was such overpressure inside the pipes, that during start up, in some detected leakages the inside out flow was observed.

This situation can be explained by engine operation. According to the information from tugboat crew, the engine works in high air excess mode. The same amount of air is being taken to engine operation regardless the engine load. Part of it is used for fuel combustion process, while the rest is guided outside together with flue gas.

The above presented mechanism may also explain relatively low NO_x concentrations, however inlet NO_x concentration corresponds to engine load status. Also for 100% engine load much higher temperatures were observed.

NO_x removal efficiency calculated for high efficient scrubber application (NOx calculated in Figure 9) is higher, than NO removal efficiency, however with almost the same character of dose dependence, for the available scrubbers (like provided by Ecospray) total removal efficiency may reach 99 %.

Observed NO_x removal rates may be explained by low doses applied. As it was mentioned before one of two accelerators was out of order, therefore only half of possible dose was available and uniform dose distribution was not assured, due to low energy electrons treated gas penetration range. Part of gas stream flowing opposite to the window get low absorbed dose. As NO oxidation and further absorption strongly depends on the absorbed dose, such situation decrease NO removal rates.

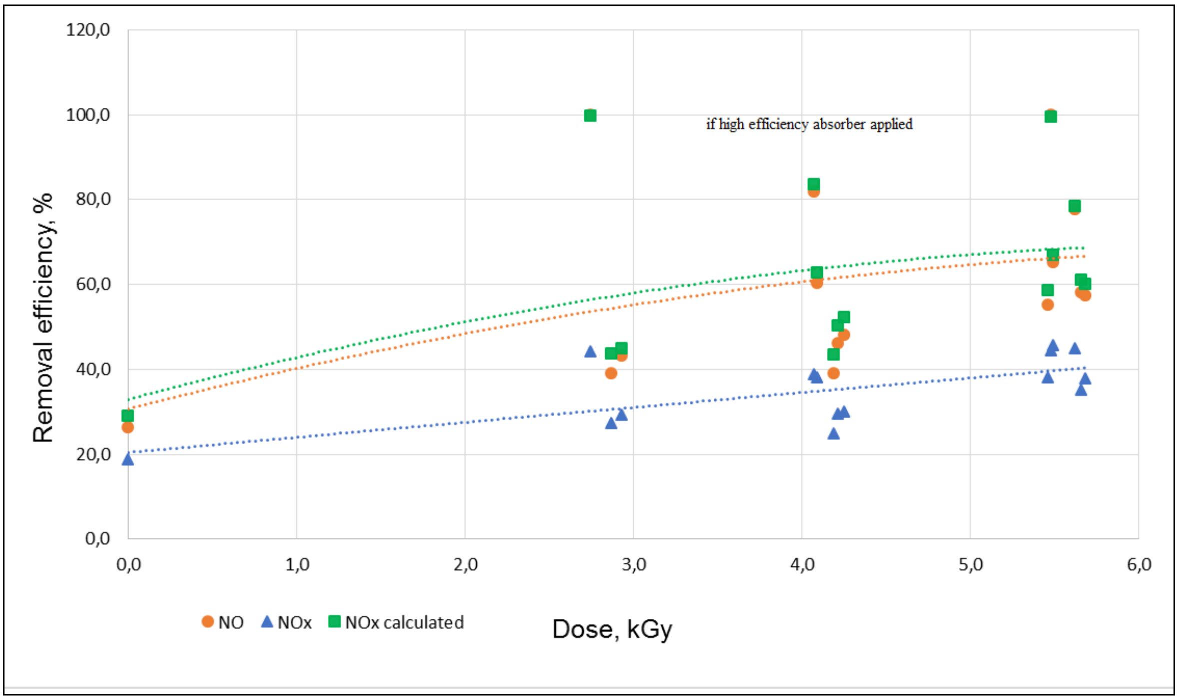


Figure 9. Dose dependence of NO and NO_x total removal efficiency for all experimental points.

As the NO_x removal was examined for different engine loads and different concentrations of oxidant the impact of this parameters should be discussed. The Figure 10 and Figure 11 show dependence of NO and NO_x removal on dose for 50% and 100% engine load respectively, while Figure 12 presents comparison of NO_x removal efficiency on dose for both engine loads.

This dependence seems to be much higher for 100% load, however there were only three experimental points recorded for this load. On the other hand, these results are close to the removal efficiencies obtained for 50% load (see Figure 12*).* That suggests, that engine load impact on the process is not too high.

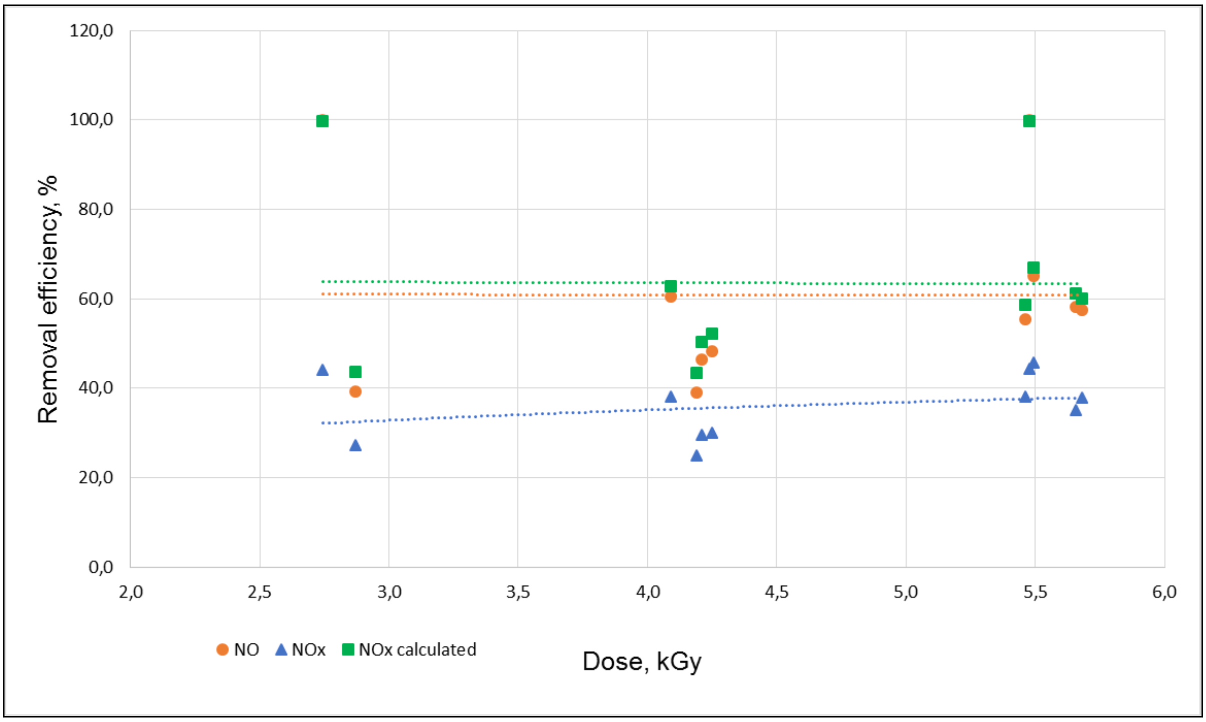


Figure 10. Dose dependence of NO and NO_x removal efficiency for 50% engine load.

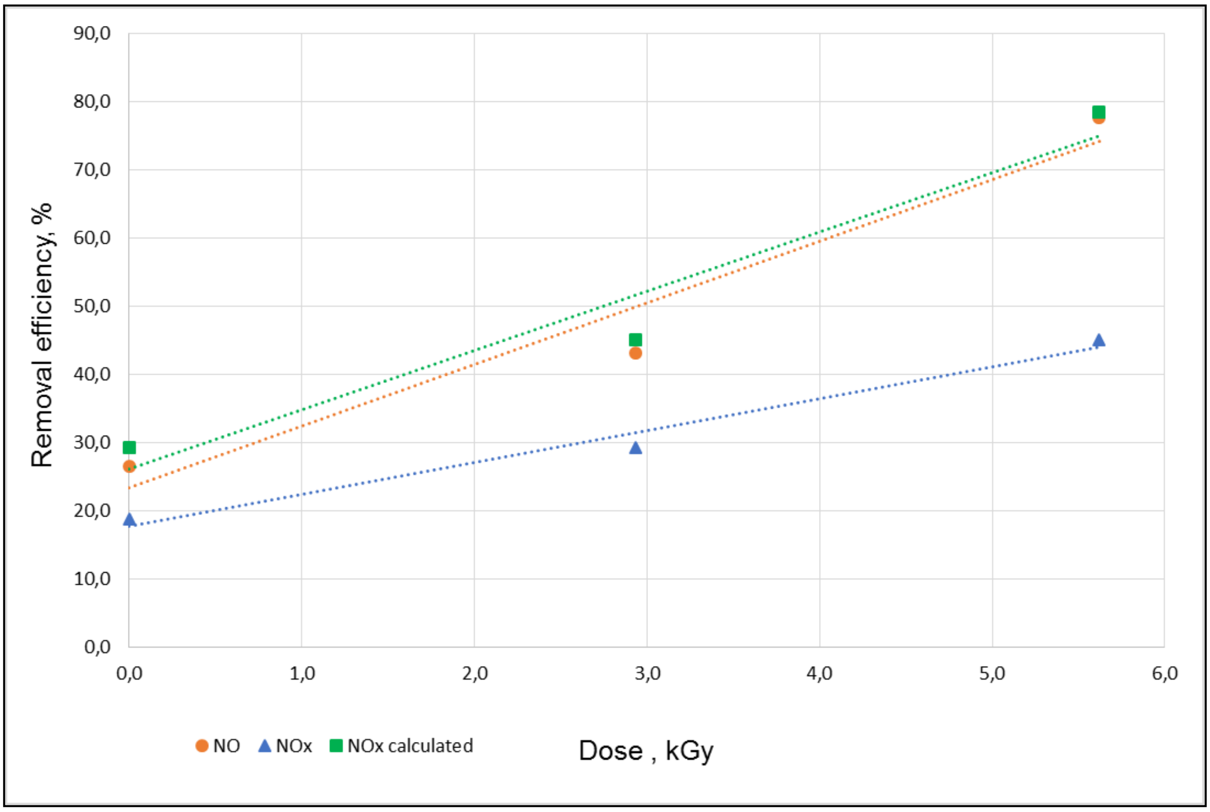


Figure 11. Dose dependence of NO and NO_x removal efficiency for 100% engine load.

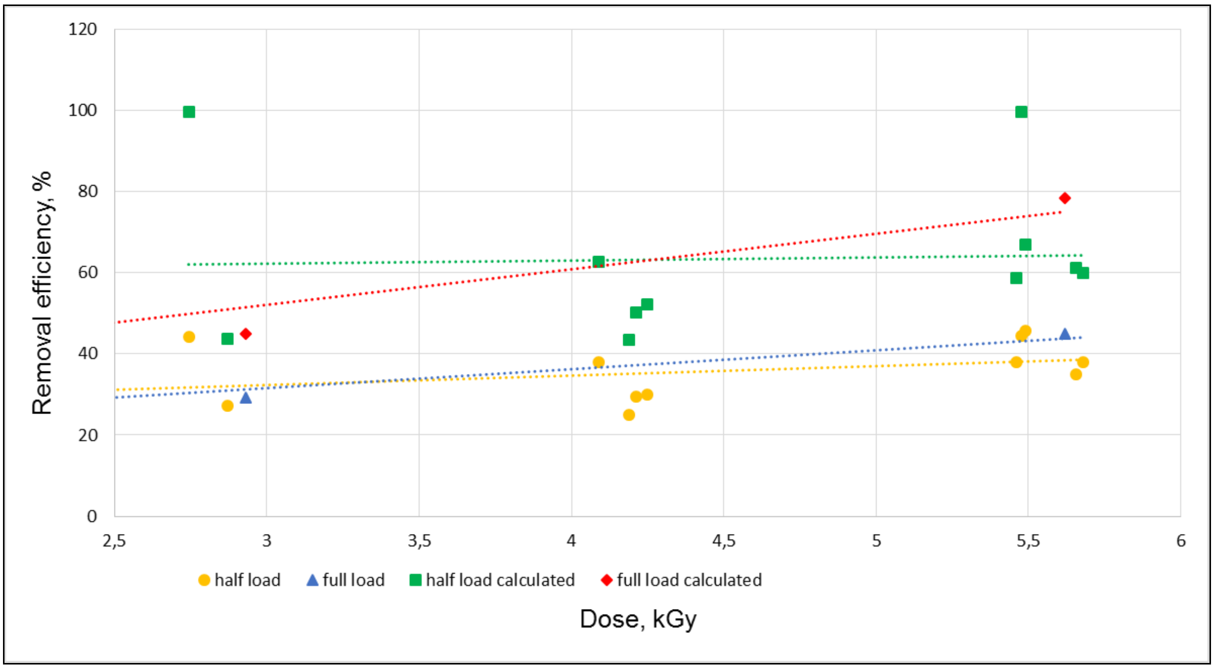


Figure 12. Dose dependence of NO_x removal efficiency for 50% and 100% engine load.

On the other hand the increase of oxidant concentration in the process water in the scrubber has strong positive impact on NO_x removal efficiency (*Figure 13*).

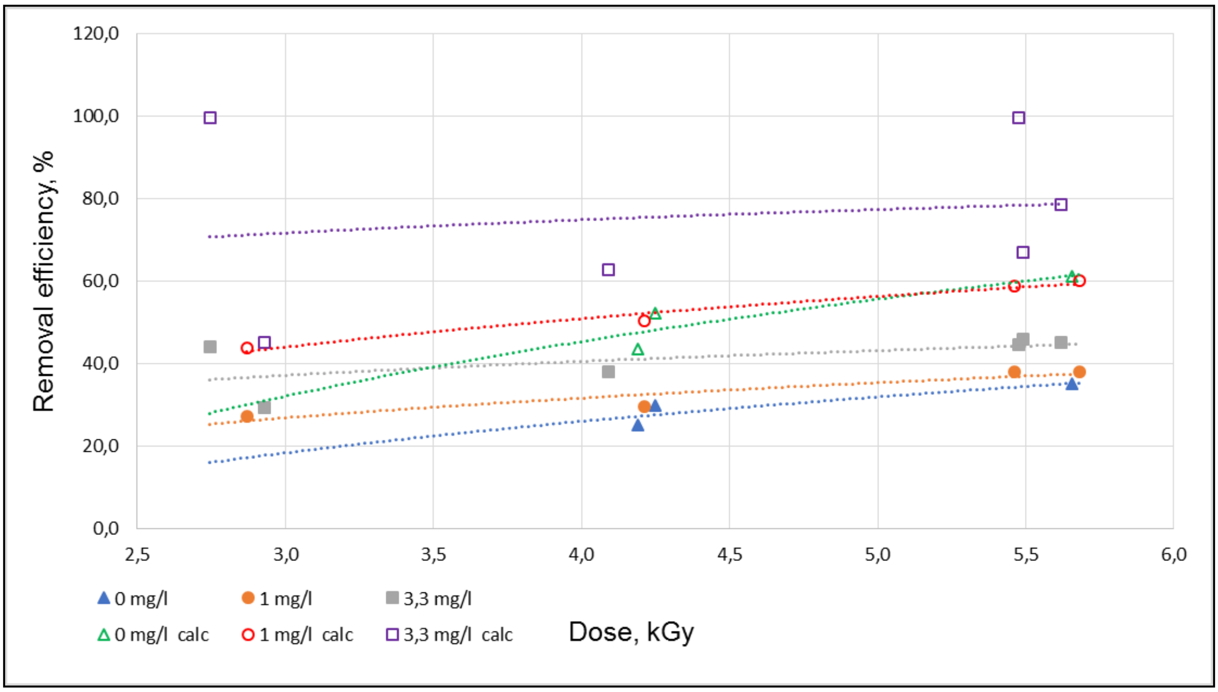


Figure 13. Dose dependence of NO_x removal efficiency for different concentrations of oxidant.

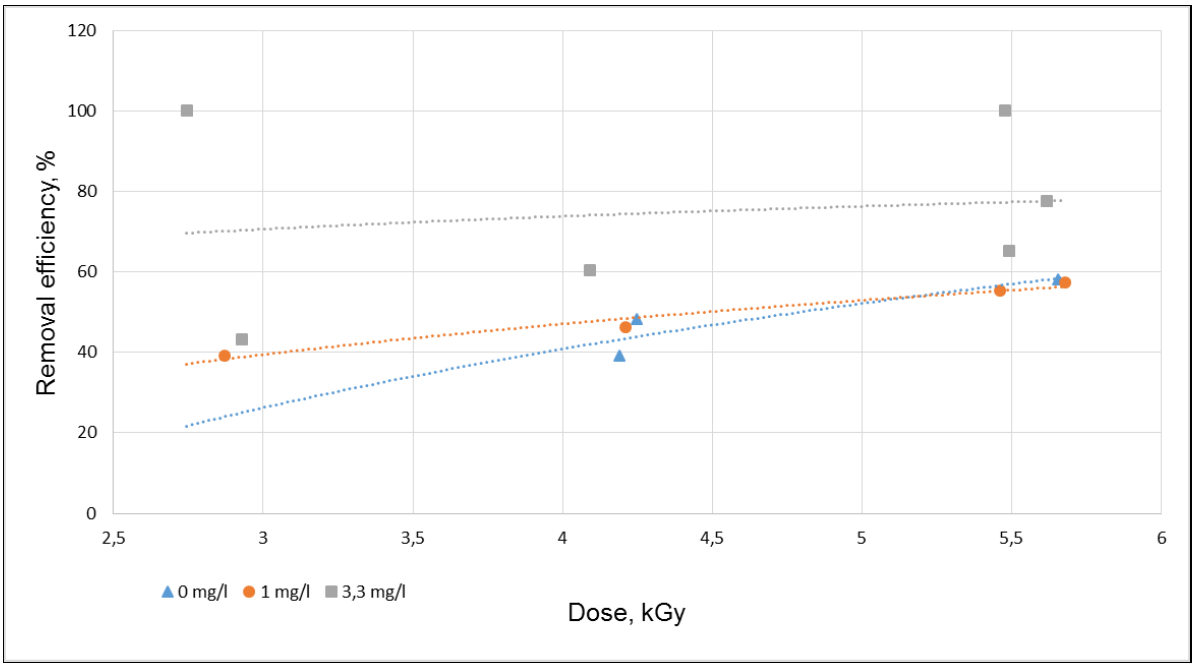


Figure 14. Dose dependence of NO removal efficiency for different concentrations of oxidant.

The same situation is observed in the case of NO *(Figure 14*), however the effectiveness of NO removal for 0 and 1 mg/l of $NaClO_2$ is very close. That suggests, that there is an oxidant concentration threshold over which the impact of oxidant presence in the water is noticeable. As it was discussed before theoretical NO_x removal efficiencies for high efficient scrubber application (NOx calculated in Figure 13) correspond with NO removal efficiencies.

According to the theory of the process, the effectiveness of NO_x removal should decrease with inlet NO_x concentration increase. This effect is observed in the obtained as well as in calculated results (see *Figure 15*), however is not too big.

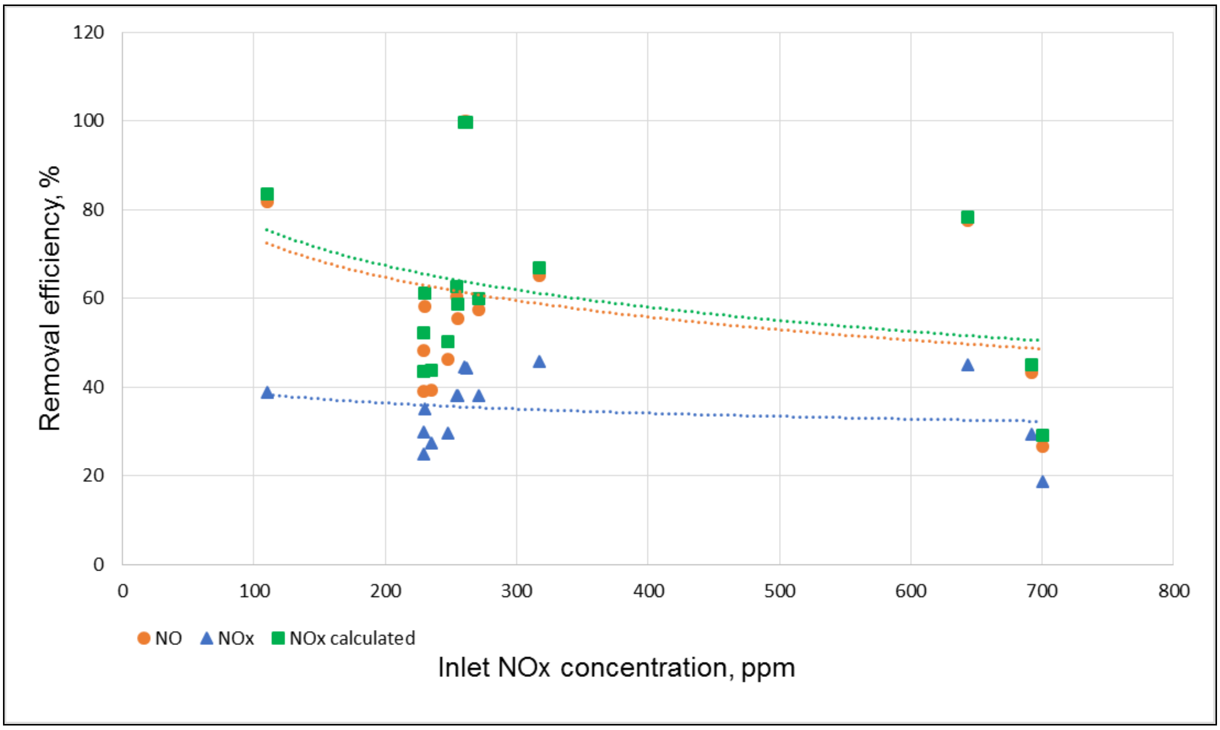


Figure 15. The dependence of NO_x removal efficiency on inlet NO_x concentration.

The removal efficiency slightly decreases with temperature increase (*Figure 16*), however this effect is not obvious, especially that the experimental points are grouped in two regions and show great dispersion for small temperature changes. Both the effects (temperature and inlet NO_x concentration) shall be further examined to verify the obtained results.

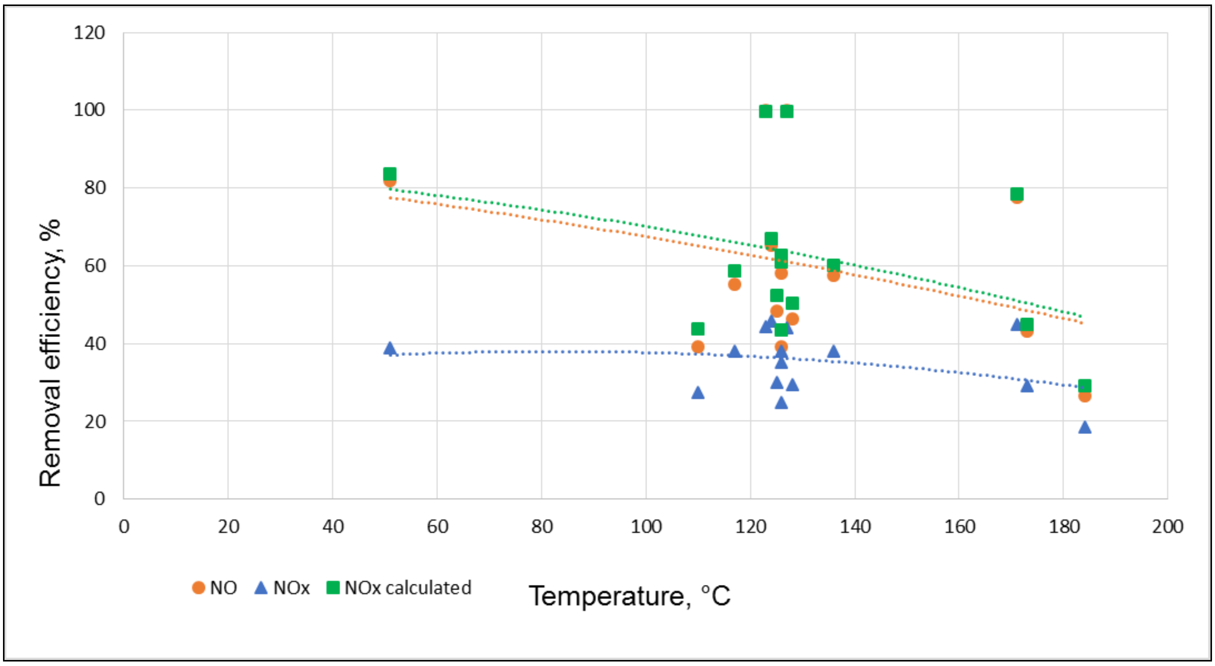


Figure 16. The dependence of NO_x removal efficiency on temperature.

6. Closed loop solution composition

In order to determine closed loop solution composition, the samples of this solution were collected during the experimental cycle. The samples were collected at the beginning and after each series of experiments. At the beginning, the tanks were filled with 3 m^3 of seawater, than 90 kg of salt (NaCl) were added and test run of the facility was done for about one hour without electron beam irradiation. During this this procedures three samples were collected – pure Baltic seawater (sample 00), solution after dissolving of NaCl (sample 01) and solution after test run (sample 02). Next two samples (coded 11 and 12) were collected after first series of experiments carried without the oxidant. Than the samples (coded 21 and 22) were collected after second series of experiments carried with 3 kg of oxidant ($NaClO_2$) added to the solution. After third series of experiments carried with 10 kg of oxidant added to the solution, the samples coded 011 and 012 were collected. These samples were also black samples for organic pollutants determination. After collection of the samples of the gas for organic pollutants determination, the last samples coded 021 and 022 were collected.

Analysis of cations and anions in local sea water and scrubbing solution were performed using ASA and ion chromatography methods. The obtained results are given in Table 6 and Table 7.

Table 6. Cations detected in wet scrubber solution.

Sample code	Description	pH	Concentration [mg/l]			
			Na^+	K^+	Mg^{2+}	Ca^{2+}
00	Pure Baltic seawater	7,45	766.03	48.5	101.5	74.8
01	Baltic seawater + NaCl	7,60	4034.3	88.0	120.9	93.5
02	After test run	6,67	10445.5	94.9	114.2	74.3
11	After first series of experiments – without oxidant	8,30	11807.7	152.2	106.0	78.7
12			11454.5	117.1	105.2	83.2
21	After second series of experiments – with 1 mg/l $NaClO_2$	7,40	12684.4	149.4	115.6	82.7
22			12583.2	148.5	111.2	77.0
011	After third series of experiments – with 3.3 mg/l $NaClO_2$	7,84	9895.1	149.3	131.0	63.8
012			10313.2	156.0	138.8	77.9
021	After collection of samples for organic compounds determination – with 3.3 mg/l $NaClO_2$	7,45	11443.5	178.4	148.3	85.6
022			11105.7	190.5	147.8	81.9

Table 7. Anions detected in wet scrubber solution.

Sample code	Description	pH	Concentration [mg/l]					
			Cl^-	NO_2^-	NO_3^-	SO_4^{2-}	ClO_2^-	ClO_3^-
00	Pure Baltic seawater	7,45	1549		8	210		
01	Baltic seawater + NaCl	7,60	7944		6	211		
02	After test run	6,67	24374		21	274		
11	After first series of experiments – without oxidant	8,30	24580	**237**	108	332		
12			26251	**276**	132	340		
21	After second series of experiments – with 1 mg/l $NaClO_2$	7,40	24888		393	308	28	372
22			27198		384	332	34	353
011	After third series of experiments – with 3.3 mg/l $NaClO_2$	7,84	28748		867	482	25	744
012			27749		843	462	36	696
021	After collection of samples for organic compounds determination – with 3.3 mg/l $NaClO_2$	7,45	24124		1143	441	13	530
022			25342		1249	462	16	576

Baltic seawater is slightly basic (pH 7,45) of low salinity (less than 0.5%), therefore sodium chloride was added to increase salinity above 3% as it is in most seawaters. The concentration of chlorides, sodium and potassium doesn't change significantly during the experiments. The only exception is sample 01 collected after salt addition, that shows much lower concentration of these ions, however it may be explained by not sufficient mixing of the solution in the beginning of experiments. Also calcium concentration doesn't change even after salt addition. That means that this ion originates from seawater.

During experiments the concentrations of nitrates and sulfates in the solution increase due to absorption process. It is characteristic, that during the experiments carried without the oxidant some amount of nitrites is observed. After oxidant addition these ions are not observed any more. That confirms the oxidation process in the solution.

The concentration of ClO_2^- decreases, as the oxidant is consumed during the process. On the other hand the concentration of ClO_3^- increases, that points out more complex chemical mechanism of the process. Process chemistry is now under elaboration.

7. Comparison with selected laboratory results

The research on application of electron beam flue gas treatment technology for purification of marine Diesel flue gases has been carried in Institute of Nuclear Chemistry and Technology for a few years. During this time technological concept of the process was elaborated as well as laboratory studies were performed. Beneath, the selected results of these works are presented as a background for evaluation of the results of Riga pilot hybrid electron beam marine flue gas treatment facility operation.

The preliminary research were realized with use of bubbling washers as an absorber after irradiation (two single equilibrium step unit). The flue gas was generated in the process of light fuel oil combustion with use of oil burner type Jet 4.5 produced by Körting Hanover AG, Germany. In order to obtain required concentration of pollutants, SO_2 and NO were added to the gas from steel cylinders. After that the gas was irradiated by electron beam generated by ILU-6M electron accelerator, Russia and guided to absorbers. The scheme of the laboratory absorption system is presented in Figure 17.

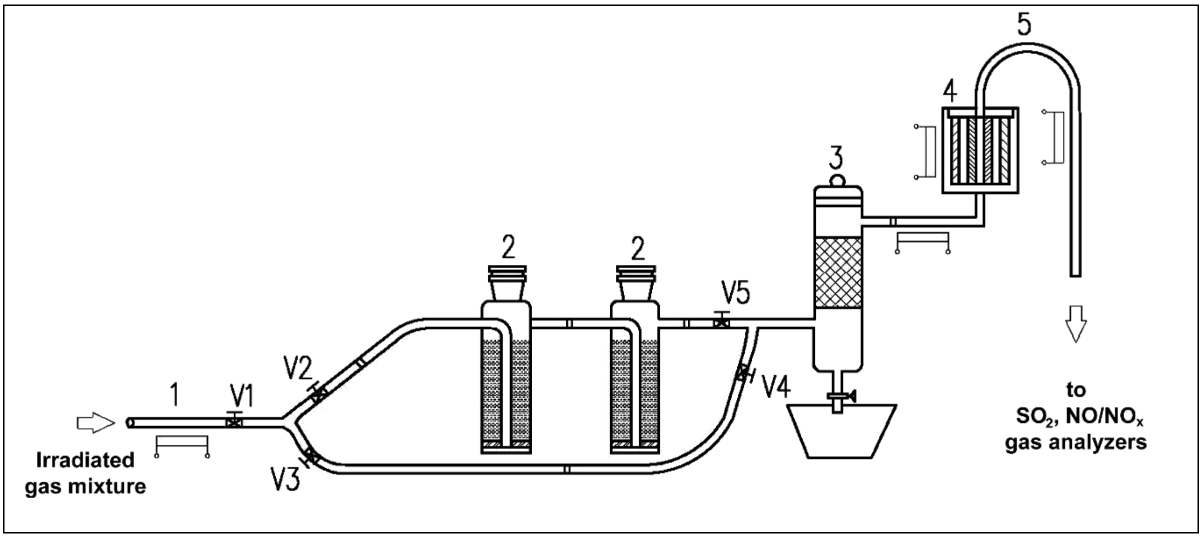


Figure 17. Scheme of the laboratory seawater scrubber arrangement

1 - heated sample probe,
2 - bubbling washer filled with seawater,
3 - demister,
4 - heated ceramic filters,
5 - heated sampling line.
V1, V2, V3, V4, V5 – shutoff valve manually operated.

The experiments were performed for flue gas contamination similar to two strokes Diesel engine i.e. 500 – 700 ppm of SO_2 and 1000 – 1700 ppm of NO_x. During the first stage of the research the impact of water scrubbing of pollutants and water salinity effect was measured the results are shown in Figure 18. It is clearly seen, that combination of irradiation with wet scrubbing has strong positive effect on NO_x removal efficiency. This effect increases noticeably with water salinity increase. The removal efficiencies for 3.5% water salinity are similar to the numbers obtained during pilot plant operation, however these laboratory research were performed without any oxidant.

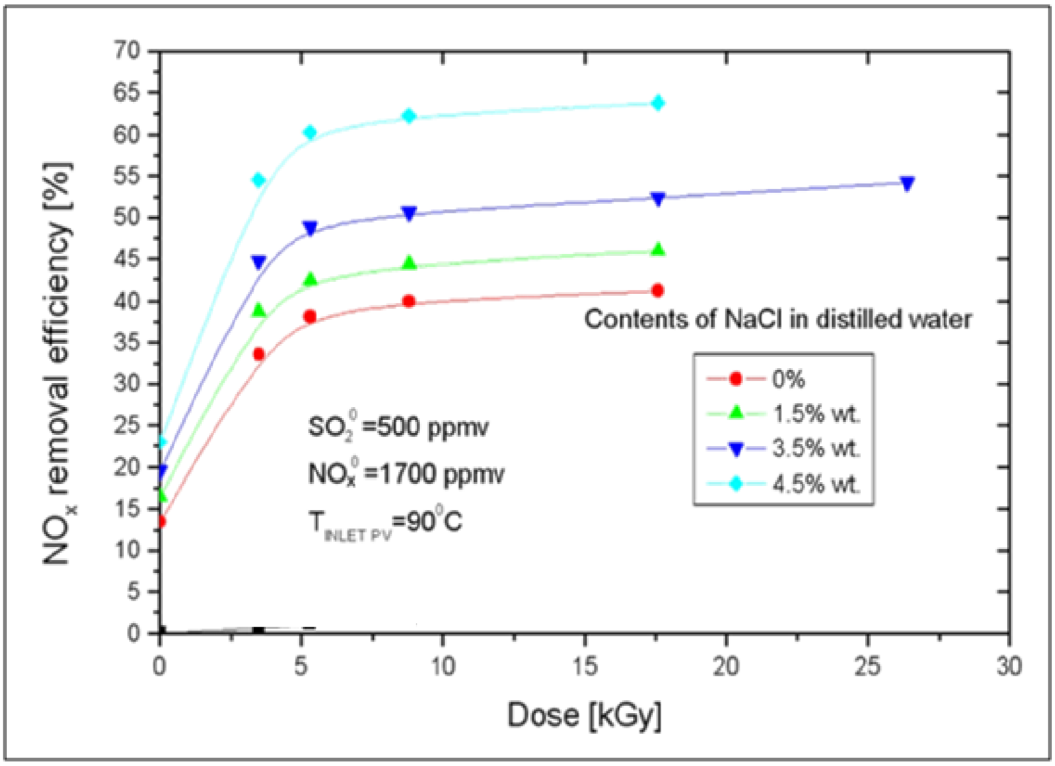


Figure 18. Effect of seawater salinity on the NO_x removal efficiency obtained in the e-beam process combined with seawater scrubber.

Moreover during these research, the impact of temperature on process efficiency was examined. The study was performed with three values of gas temperature: 70°C, 90°C and 100°C. Figure 19 presents effect of gas temperature on the NO_x removal efficiency. Although the temperature has also positive effect on NOx removal efficiency, it is not very strong.

Therefore the temperature shall be kept at maximal possible value with regard to technological issues as temperature resistance of accelerator window or cooling system.

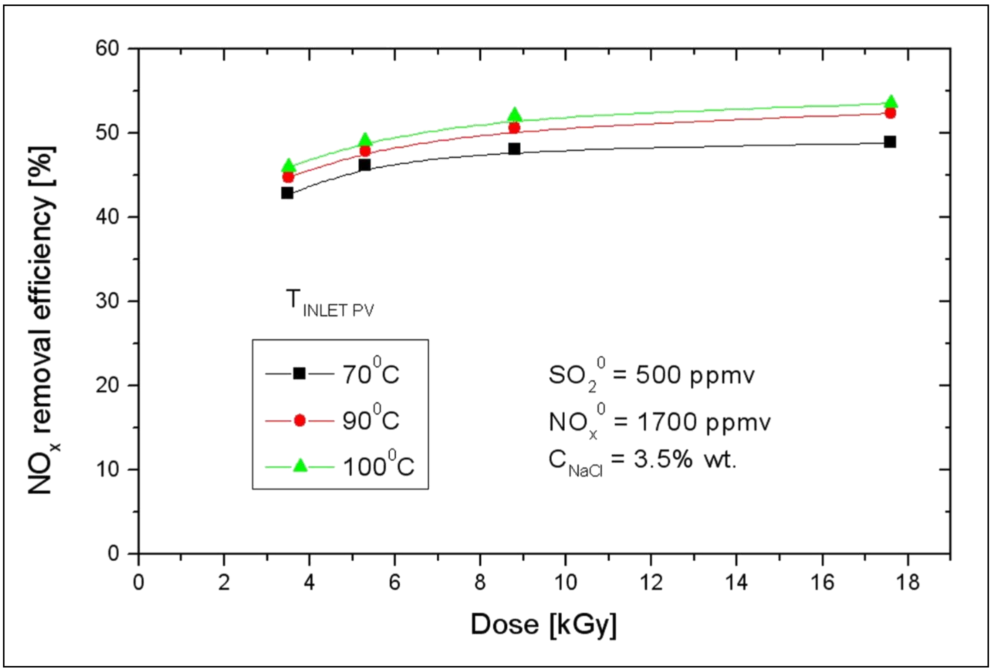


Figure 19. Effect of gas temperature on NO_x removal efficiency for laboratory research on e-beam process combined with seawater scrubber.

The impact of oxidant addition is clearly seen in Figure 20. In this case 5 mM concentration of $NaClO_2$ was applied. In this case the obtained removal efficiencies are considerably higher than the results of Riga pilot plant operation. On the other hand during operation of Riga pilot plant operation one of the accelerators was broken, that resulted in lowering of the dose and non-uniform dose distribution in the reaction chamber (Figure 21). Moreover quite low concentration of oxidant (3,3 mg/l) were applied during Riga experiments. Figure 22 shows the correlation between oxidant concentration and NO_x removal efficiency obtained for laboratory experiments. It might be expected, that for higher oxidant concentration and more uniform gas irradiation the NO_x removal efficiencies will be much higher.

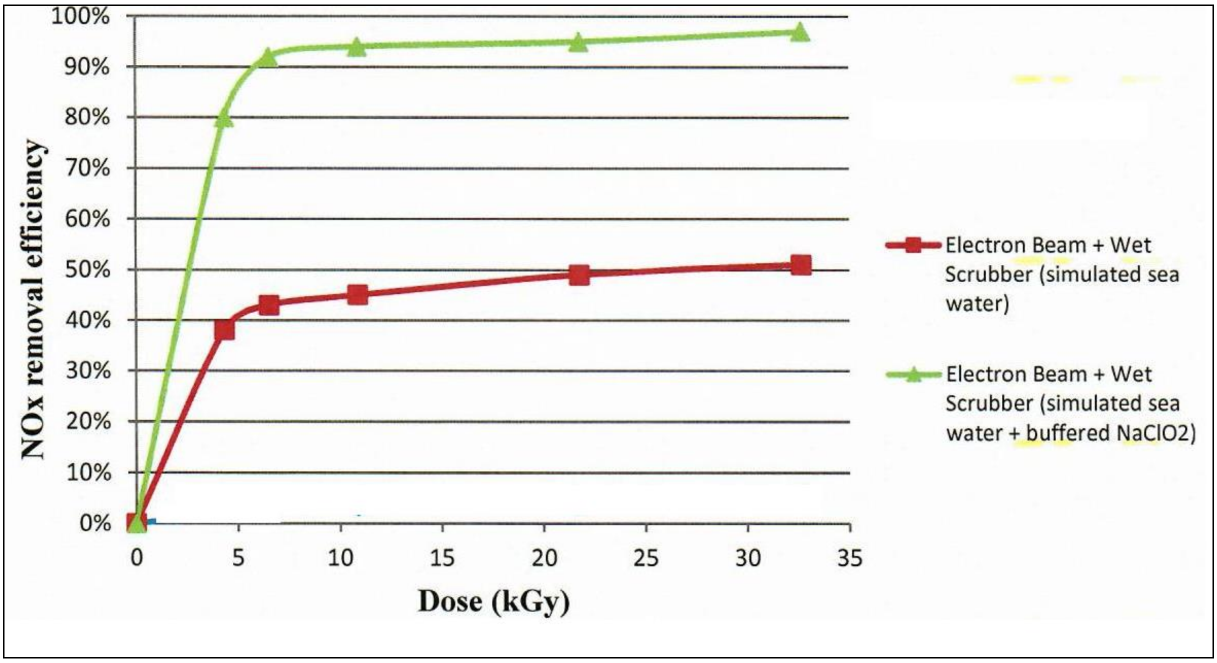


Figure 20. Comparison of laboratory research results obtained for electron beam process combined with wet scrubbing and electron beam process combined with wet scrubbing with oxidant addition.

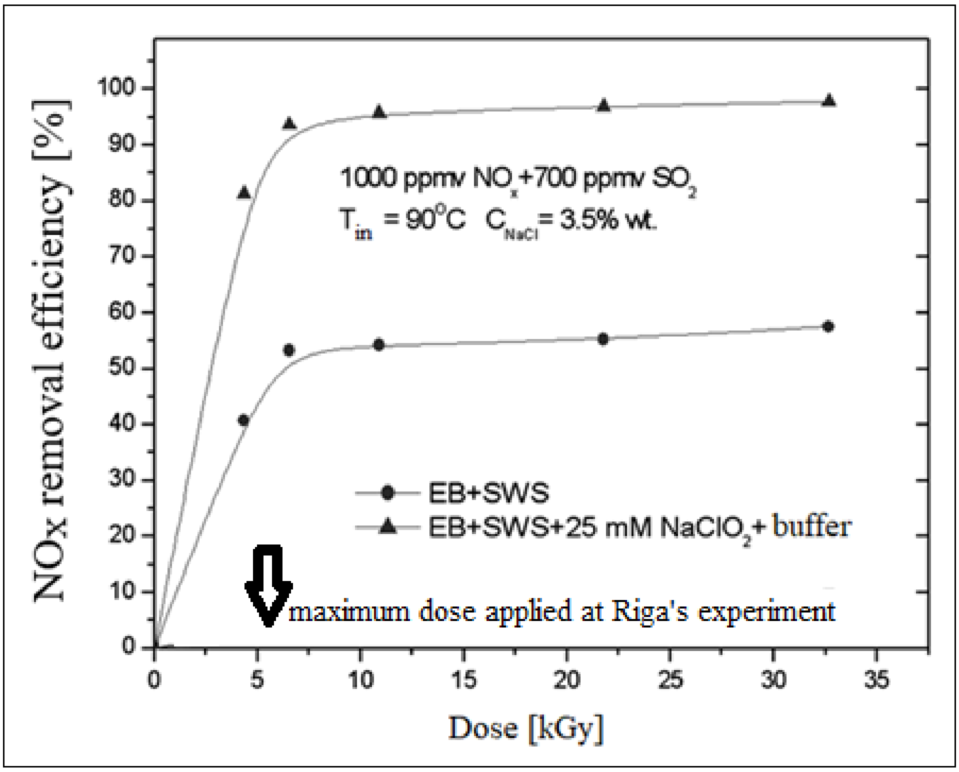


Figure 21. Comparison of results obtained in laboratory experiments with Riga pilot plant operation results should be done with regard to the fact, that maximum dose reached at Riga's experiment was 5.6 kGy., and gas from ship's diesel engine was SO_2 free.

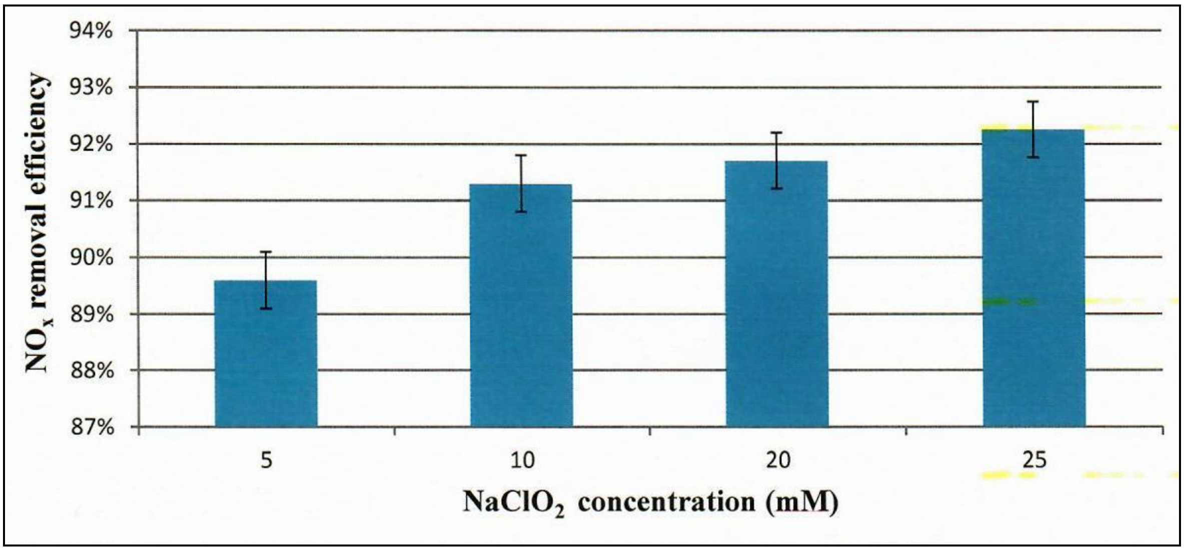


Figure 22. Effect of oxidant concentration on NO_x removal efficiency.

During laboratory research, it was found, that for high inlet NO concentration this parameter has almost no impact on total NO_x removal efficiency (Figure 23). As during Riga pilot plant operation it was found, that the removal efficiency slightly decreases with inlet NO concentration increase, this effect shall be verified during further research.

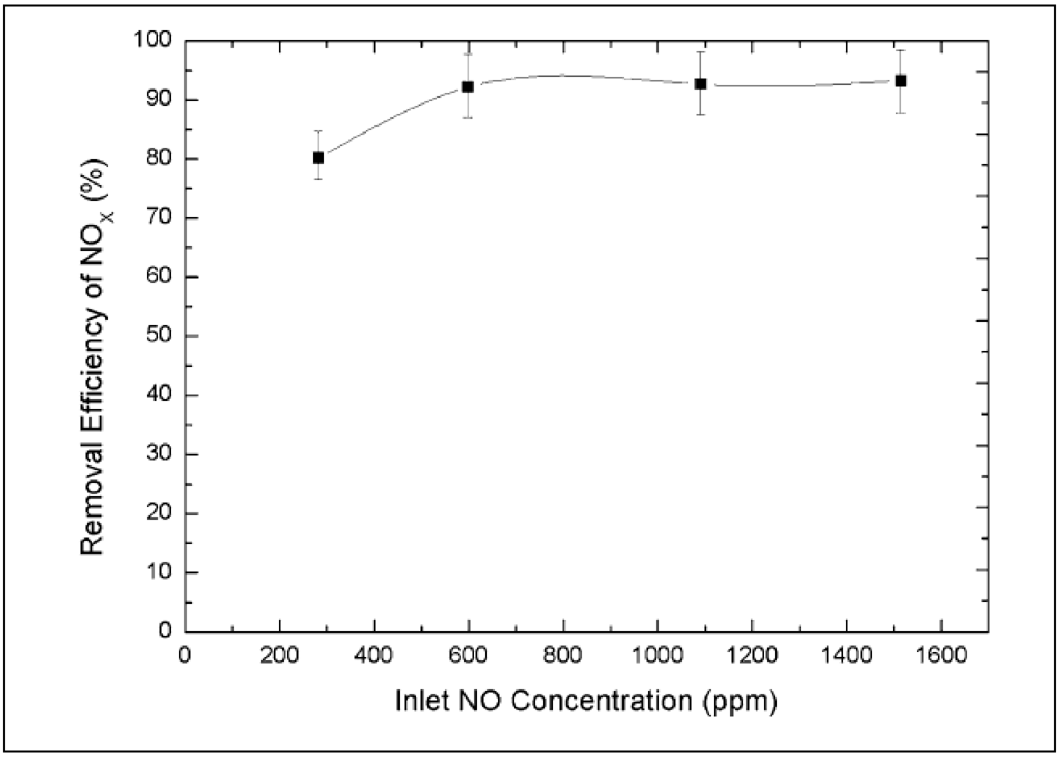


Figure 23. Influence of inlet concentration of NO for the NO_x removal in the sea water–NaOH – $NaClO_2$ wet scrubber aqueous solution (fixed absorbed dose 10.9 kGy).

8. Final remarks

On the basis of the results of the experiments performed on the pilot hybrid electron beam flue gas treatment plant located in Riga Shipyard, the following remarks may be formulated:

1. There were not technical and operational possibilities to apply solutions required for designed novel hybrid system testing covering all its components. No spray was introduced to the irradiation zone (due to the fact that existing FEP accelerator for grain seeds irradiation had to be used) and only one side irradiation has been applied (only one side accelerator was operational during the tests). The two stage installation was tested; diesel engine – inlet pipe – accelerator irradiation zone – inter stages pipe – packed absorption column – outlet pipe.
2. The tests were performed for NO_x containing ship Diesel off gases. The operation of the plant was the first case of examination of the hybrid electron beam technology in the real conditions. Taking in account the experiment conditions, good agreement was obtained with laboratory tests in the maximum available at field test dose range.
3. Due to the fact that most important in this experiment was testing integration of diesel engine with accelerator and scrubber, such arrangement was demonstrated for real field condition and was fully operational. Single window (laboratory installation is equipped in double window system as were other INCT installations for flue gas treatment at coal and oil fired plants) with air protective stream curtain system was tested and positive results allows to apply such solution in on board applications. The observations taken during the field tests will be applied in the engineering of process vessel exclusively being applied for ship off gases treatment (for reported field tests available FEP unit, regularly used for seeds treatment, was applied). The toroidal accelerator will provide uniform dose distribution.
4. Closed loop system was tested and such system operation was demonstrated during the experiment. Application of closed loop system is obligatory in further implementation of hybrid electron beam technology in marine conditions.
5. The construction and operation of pilot hybrid electron beam flue gas treatment plant located in Riga Shipyard showed ability of the technology to be used in

marine conditions. The combination of accelerator technology with wet scrubbing process is a good solution for simultaneous treatment of SO_x, NO_x and PM from marine Diesel engine flue gases. Although short, successful test in Riga's Shipyard has demonstrated results which opens opportunity to follow up works related to on board testing.

6. Both systems, electron accelerator unit and scrubber require further development and optimization towards their use at on board implementation.

Annex III

PROOF OF
CONCEPT FUND

REPORT

ON IMPLEMENTATION
OF WP5 TASKS

Table of Contents:

1. General description - introduction

This study was created as part of the WP5 task - economic analysis in the project "**Development of a hybrid electron accelerator system for the exhaust gas treatment of marine diesel engines**"
The task of WP5 is to perform a comprehensive business, economic and financial analysis by the consortium member, BIOPOLINEX, from the point of view of the end user and from the point of view of the manufacturer of the hybrid electron accelerator system for the exhaust gas treatment of marine diesel engines. The investment profitability will be assessed on the basis of discounted cash flows, NPV[1], IRR[2] and repayment period. The breakeven point[3] will be calculated. A sensitivity analysis of the volatility of key financial parameters will be carried out.

2. Characteristics of the issues covered by the project

From January 1, 2020, all waters except ECA will have a 0.5 percent m/m[4] limit of a sulfur in a fuel. The exception will be ships equipped with exhaust after-treatment systems. In this case, it will be possible to use high sulfur fuel, but it will be necessary to monitor the composition of the exhaust gases.
Worldwide fuel production with low sulfur content is also a problem. It turns out that the demand for such fuel is greater than production capacity. This fuel is not only used to power passenger ships, but also other sea ships. According to available data, over 50 000 oceans float ships, of which 300 are cruise variants. This shows how big the scale of the problem is.

In the interests of the environment, the International Maritime Organization (IMO) has tightened standards for sulfur content in fuel used in ships in controlled emission areas (ECA - Emission Control Area). According to current regulations, the permissible sulfur content in the fuel dropped from 1.00 % to 0.10 %. A 10-fold decrease in the permissible sulfur content in fuel forced ship-owners to take appropriate measures to meet the standards.

[1] NPV - Net Present Value. Comprehensive description on page 13.
[2] IRR - Internal Rate of Return. Comprehensive description on page 14.
[3] Breakeven Point (BEP) - is determined by dividing the total fixed costs associated with production by the revenue per individual unit minus the variable costs per unit.
[4] % (m/m) - mass percentage concentrations

The most commonly used technical solutions used to meet emission standards include:

- supplying the main engine and auxiliary equipment with fuel with reduced sulfur content,
- reducing sulfur oxides emissions by installing flue gas scrubbers,
- installation of dual-fuel engines running on liquid and gas fuels,
- conversion of the ship's propulsion into hybrid, electric-combustion.

Each of the presented solutions has its advantages and disadvantages. The use of some of the presented installations requires significant rebuilding of the machinery room. This is sometimes associated with a reduction in the ship's cargo space. In turn, the simplest solution, the use of low-sulfur fuel affects the increased wear of injection system components.

The solution shown in the project is a new, hybrid technology, based on the concept of combining two methods used to clean up the exhaust gases: Electron Beam (EB) and Improved Wet Scrubbing. This hybrid technology has a great potential to solve the emerging problem of marine industry, although it still requires research. Taking under consideration all of the advantages of the technology in comparison to other available methods, hybrid technology may become a promising and cost-saving option in the future marine market.

The choice of the best solution depends on the specificity of the watercraft and the work it performs.

3. Overview of available solutions and ways to reduce pollution

There are many technical and operational methods available to reduce emissions from the ships operated today[5]:

- Low sulfur fuels,
- Scrubbing,
- Fuel water emulsion,
- Humid air motor,
- Direct water injection,
- Exhaust gas recirculation,
- Selective catalytic reduction (SCR),

[5] Based on: Paulauskas V., Lukauskas V.: Sustainable Shipping and Port Development, CLEANSHIP Project Task 3.6, http://www.clean-baltic-sea-shipping.com.

- NOx traps,
- Selective non-catalytic reduction.

The problem is that none of mentioned methods let reduce both SOx and PM in shipping emissions. SOx in emissions may be reduced only with scrubbers and low sulfur fuels and other methods reduce only NOx.

At present scrubbers and Selective Catalytic Reduction (SCR) systems are most developed and implemented technologies.

Scrubbers which are used on ships may be of two types: dry scrubbers or wet scrubbers (seawater open loop, fresh water closed loop and hybrid).

Scrubbing system can be modified in up to about 40% of floating ships because of limited space available.

Besides there are no economic substantiates to modify scrubbing system on ships older than 20 years.

Low sulfur fuels

A 10-fold decrease in the permissible sulfur content in fuel forced significant changes on ship-owners. There are several ways to meet the requirements of IMO. The first option to adapt marine engines to meet the standards imposed by the sulfur directive is to supply the ship's engine with light fuel (LSMGO - *Low Sulfur Marine Gasoil*) instead of MDO (*Marine Diesel Oil*) or IFO (*Intermediate Fuel Oil*).

Nr	Fuel name	Sulfur content [%]	Price [USD]	Price [EUR]
1	IFO380	3.00	388.50	355.12
2	LSMGO	0.10	607.50	555.30
		Difference	**219.00**	**200.18**

Table 1 - *Fuel prices*

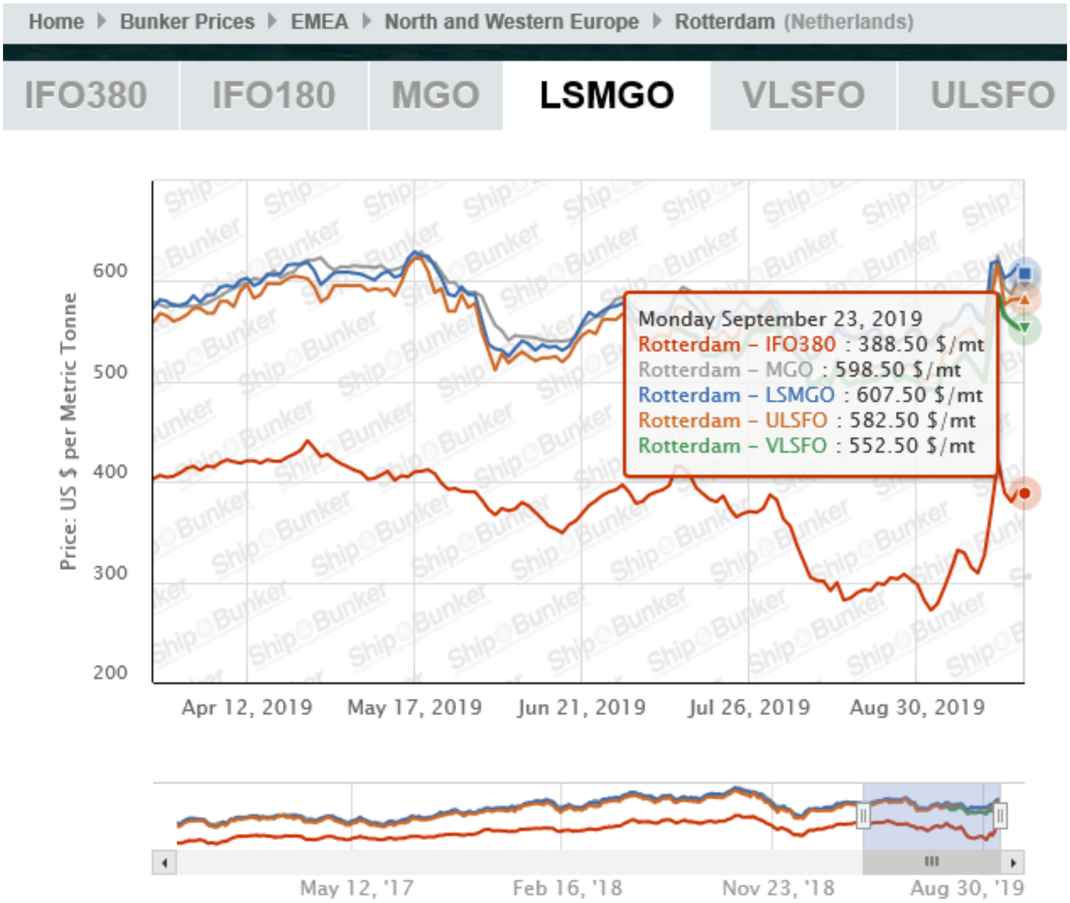


Chart 1 - *Average fuel prices at the port of Rotterdam in 2019, along with prices on September 23, 2019*

The prices of low sulfur fuel are much higher than the prices of high sulfur fuel.
LSMGO fuel with a permissible sulfur content of 0.1%, which is required in controlled emission bodies, in September 2019 cost $ 219 more per ton than IFO380 with a sulfur content of 3%.
Large Atlantic ships, on uncontrolled water areas, use high sulfur fuels to save money. Entering the waters with more stringent requirements as to the quality of exhaust gases, they are forced to change the fuel supplying the main engine and all auxiliary engines of power generators, or the fuel supplying the ship's boiler.
Many publications emphasize the financial problem related to the change of fuel used to supply the ship, however, taking into account the very small percentage of such ship's voyage time in the controlled emission area, the need to use more expensive fuel for a relatively short time does not increase the ship's operating costs significantly, and hence, freight prices.

The biggest problem is strictly connected with the technical side of the entire adjusting of the fuel supply source for engines and equipment on board. The transition from heavy sulfur fuels is a big challenge for ship equipment. Standard high sulfur fuel has much better lubrication properties than low sulfur fuel.
The lubricating properties of the fuel are extremely important in the operation of moving parts of the fuel system. These include injection pumps, injectors and fuel transport pumps. Deterioration of the lubricating properties of the fuel causes the possibility of destruction of injection pumps and injectors due to seizure of precision vapors of the mentioned devices. This results in very expensive repairs, involving the regeneration of injection pumps or injectors, and in extreme cases it is necessary to replace the element with a new one.

Due to the decreasing fuel density, the ability to self-ignite fuel increases when using low sulfur fuels. This is a serious obstacle when using these fuels to power marine boilers and always involves the need to regulate the boiler's air supply.
In some cases, there's a must to replace a burner for further proper operation of the boiler. The higher ability to self-ignite fuel also causes problems in the operation of engines on board. Adjustment of the injection pumps is required. It is a relatively easy process on modern units equipped with electronically controlled common rail fuel injection. In this case, injection adjustment is quick and carried out remotely. In older designs, each injection pump of a given cylinder should be adjusted. The number of injection pumps depends on the number of cylinders. For the crew, this means a lot of work when adjusting each of them.
In the case of ships only in areas where it is necessary to use fuels with a limited sulfur content, the engines are constantly fed with low sulfur fuel. This is the case, for example, on ferries sailing on the Baltic Sea between Poland and Sweden.
In this situation, ship-owners are forced to carry out modernization of the ship's power plant, allowing the safe combustion of low-sulfur fuels.

Scrubbers - exhaust gas washers

When a ship navigates only in areas covered by the Sulfur Directive, it is profitable to install scrubbers, i.e. exhaust gas washers. It enables to supply the engine with fuel with a higher sulfur content, and the quality of the gases emitted to the atmosphere is supervised by a scrubber cleaning the exhaust gas flowing through the exhaust gas outlet.
There are two methods for cleaning exhaust gases by means of scrubbers.

The first is the installation of a wet scrubber. In this solution the exhaust gases flow through a sprayed water cloud, which is designed to absorb sulfur particles. The scrubber design allows installation in an open, closed or hybrid system, which is a combination of an open and closed system.

In an open system, the exhaust gases are flushed through outboard water, which, after passing through the scrubber, is pumped into the sea. Sea water has the natural ability to absorb sulfur oxides (SOx).

In a closed system, the flushing water circulates in a closed circuit and requires chemical treatment.

Exhaust gas scrubbers are not individual devices, but very complex systems, which often take up a lot of space on the ship. The main part of the installation is located in the chimneys of a ship and such interference is always associated with the extension of the exhaust gas outlet.

In a typical configuration, additional scrubber equipment, such as pumps, separators, tanks, control rooms, are located in the ship's engine room. As the ship builder did not foresee such an installation in the original design, the room of the engine room should be enlarged usually at the expense of the hold. This solution also has its advantages, because the low placement of additional devices balances the weight of scrubbers mounted high in the chimneys.

If an appropriate project is made and enough space is provided in the ship's hull, the installation of a scrubber turns out to be a very good solution. It allows to meet strict standards for sulfur oxides emissions, and also reduces particulate emissions, without the need for expensive low-sulfur fuels, which in addition carries the risk of severe damage to the injection system. The above arguments decide about the great interest of ship-owners in the installation of scrubbers on ships sailing in controlled emission areas.

It is worth to mention that actually the Polish shipyards - Gdansk Remontowa S.A. and Gdynia Nauta S.A - are the precursors to the assembly of these devices. The number of assemblies carried out by three biggest port towns shipyards and their very positive effects have allowed us to achieve recognition among global ship-owners and a strong position on the global market of our domestic shipyards.

Fuel water emulsion

Invisible smoke technology is based on fuel-water emulsification (FEW), whereby the heavy fuel or diesel oil is homogenized with fresh water before injection into the engine. Apart from lowering smoke and soot emissions significantly, the system is claimed to reduce NO_x levels to[6].

Humid air motor

Humidification of combustion air used to reduce NOx emission. In the HAM unit, relatively hot and dry air from the turbocharger is mixed with the water vapour from the heat exchanger. The HAM unit replaces the intercooler and increases the humidity of the combustion air.

Direct water injection (DWI)

The method used for reduction of NOx emission by the injection of water directly into the combustion chamber via a separate nozzle: 50-60% NOx reduction with some fuel consumption penalty. The key element in the design concept is the combined injection valve through which both fuel and water are injected. One needle in the combined nozzle is used for water injection, and the other one for fuel injection. Water injection starts before fuel injection in order to cool down the combustion space to ensure low NOx formation before fuel ignition. A high pressure water pump is used to generate water pressure of 200 – 400 bar[7]. After filtration and dampening of pressure pulses, the water is fed to the injectors via a pressure regulating valve to provide the correct injection pressure. Water injection timing is electronically controlled and can easily be adjusted from a keyboard. The amount of water injected, i.e. the water/fuel ratio, is controlled by duration of injection. The DWI was an intermediary step used to comply with the Class 1 requirements. Other technologies such as NOx Reducer, exhaust gas recirculation (EGR) and Natural Gas as a marine fuel will need to be utilized in the future to meet the tighter emissions regulatory requirements.

Exhaust gas recirculation

Nitrogen oxides (NOx) emission reduction technique used in a reciprocating internal combustion engine, which involves diluting the intake air with recirculated exhaust gases.

[6] The definition of Wärtsilä Encyclopedia of Marine Technology
[7] The unit of pressure defined as 100 kilopascals (1000 hPa)

Dual-fuel engines

Dual-fuel engines have been around for years. Initially, they were mainly used to drive power generators. They are adapted for the combustion of diesel oil and natural gas CNG or LNG. The solution was successfully adapted to power the main engines of the ships.

As a result, a significant decrease in the emission of sulfur oxides, nitrogen oxides and particulates was obtained. In the era of ever-increasing requirements as to the quality of exhaust gas emissions from watercraft, dual-fuel engines have become a much appreciated construction. The two largest engine manufacturers for the maritime industry, MAN Diesel & Turbo and Winterthur (formerly Wärtsilä) have a very extensive range of dual-fuel engines, which allows the use of such a design on any type of watercraft.

In dual-fuel engines, one may see a significant improvement in exhaust gas quality when running on gas. Almost all exhaust gas parameters are improved. The largest decreases were observed during the emission of sulfur oxides (SOx), a decrease of 92% compared to a heavy fuel engine. Particulate emissions are reduced by 37%, carbon dioxide emissions are reduced by 23%, and nitrogen oxides (NOx) emissions are reduced by 12%. The quality of exhaust gases meets the stringent requirements set by the International Maritime Organization for ships sailing in controlled emission areas.

Dual-fuel engines have an extensive electronically controlled fuel system. It allows for easy automation and thus saves time. Electronic control also allows you to maximally optimize engine efficiency.

Dual-fuel engines are future-proof devices, and their further development may cause a further increase in efficiency and achieved power while maintaining very good exhaust gas quality.

Hybrid drive

It works on the same principle as in hybrid cars. The ship's batteries are charged in the port using the coastal infrastructure. In the first phase of the cruise, the ship uses only electric motors. When the batteries are discharged, an internal combustion engine is started, which drives the ship, as well as generators, which recharge the batteries for electric propulsion. The ferry overcomes the last 20 minutes of the trip using only an electric drive. This solution is used by the German-Danish ferry company Scandlines, operating the lines between Gedser in Denmark and Rostock in Germany - the entire crossing takes one hour and 45 minutes, of which only electric motors work for 40 minutes of the voyage. Energy accumulates in 2.7 MWh batteries. Unfortunately, this solution is not cost-effective to be used on ships sailing long distances.

The reason is the lack of necessary infrastructure in the ports for charging the batteries, as well as the need to make space for batteries. The cost of converting one ship into a hybrid-electric drive is estimated at 14 million EUR.

At present hybrid drive is available for a small group of ships. However, taking into account the continuous development of electric cells, increasing their capacity while decreasing their size, this alternative cannot be rejected at the moment.

In addition, when the number of units equipped with an electric drive increases, the ports will certainly not be indifferent to the needs of ship-owners and will begin to prepare their banks for charging batteries.

Below table presents a comparison of the costs of implementing the solutions presented.

Solution	Cost
Modernization of a ship onto the hybrid drive one	14 000 000 €
Use of Low-sulfur fuel	Fuel price rises up to ca. 220 € / t
Assembly of exhaust gas washers	5 000 000 €
Purchase of a dual-fuel ship	270 000 000 €

Source: *https://www.freightlink.pl/sites/default/files/marpol_infographic_v4-pl.pdf.*

Each of the presented solutions has its advantages and disadvantages. The selection of the right one depends on the specifics of the work performed by the given ship, and in particular on:

- the length of the voyage in the controlled emission area,
- for ships affecting the short term to controlled emission areas, the use of low-sulfur fuels is a cost-effective solution. For ships only in such areas it is profitable to install a scrubber,
- the possibility of modernizing the machinery room, e.g. installation of a scrubber is associated with a large expansion of the machinery room at the expense of loading space. Sometimes such modernization may prove unprofitable or impossible,
- hybrid drive use is possible only on ships operating on short distances between ports that have infrastructure for charging batteries. In addition, the batteries take up valuable cargo space,
- the purchase of a dual-fuel ship is an investment that will pay for itself after years of use. However, it should be noted that the effects obtained during the operation

of such a unit are very good. The decrease in operating costs should also be considered an advantage.

The presented methods are not the only methods used to improve the quality of exhaust gases, but they meet the high standards of the MARPOL[8] Convention, significantly improving the condition of the marine environment.

The new emerging **hybrid technology** that couples the Electron Beam (EB) with the reduced size wet scrubbing methods may provide an answer to the reducing emissions from the marine shipping industry. There are two main stages involved:

1) SO_2 and NOx oxidation during irradiation of wet gases by the EB from the accelerator and
2) the pollution products absorption into aqueous solution. Such a concept aims to enhance the advantages and minimize the limitations of each technology and achieve simultaneous removal of both pollutants e.g. the low removal efficiency when cleaning exhaust gases with high SO_2 and NOx concentrations with only the EB and the low NOx removal efficiency with absorption, etc. The organic pollutants (VOC[9], PAH[10]) may be destroyed in EB formed plasma as well. As the scrubbing solution is used salty water, easily obtainable by marine industry with the addition of the limited concentration liquid oxidant to scrub products of the reactions.

The NOx removal of hybrid technology is higher than results obtained for SNCR[11] (only low concentration of NO can be treated), ozone injection, bioprocess and other plasmas methods (EB is more energy efficient than e.g. pulsed corona discharge). The SCR[12] catalyst enables a very high removal efficiency for high NO initial concentrations, but the technology is very expensive and requires extensive amount of space. Furthermore, only NOx can be treated with this technology. The Hybrid EB method by contrast, enables a significant reduction of both pollutants in the limited reagent consumption and may assure organic pollutant destruction what may be required by new standards in the future.

Business development of this technology is directly dependent of this proof-of concept project – results of this project will demonstrate to the industry (ship-owners, shipyards, engine manufacturers) and relevant stakeholders and decision

[8] International Convention for the Prevention of Pollution from Ships of IMO
[9] VOC - Volatile Organic Compounds
[10] PAH - Policyclic Aromatic Hydrocarbon
[11] SNCR - Selective Non-Catalytic Reduction
[12] SCR - Selective Catalytic Reduction

makers, technical possibility of the electron beam accelerator application into the marine environment. Experimental results demonstrating sufficient efficiency of the SOx and NOx removal rates will be supported by the independent economic feasibility study.

Economic assessment of the above described solutions and ways to reduce pollution is not possible to make, using only general data.

As mentioned above, only 40% floating ships may be considered to upgrade the installation and that depends on technical parameters of particular ship what is a cost of such an investment.

Often there is a considerable difficulty to fit installation of wet scrubber and dry scrubbers take up even more space than wet scrubbers and are heavier. Installing scrubbers on ships already in service can be a challenge.

The exhaust gas cleaning installation significantly reduces the ship's cargo capacity, but the good part of this system is that the weight is in the low-lying parts of the ship, and thus balances the weight of the scrubbers in the chimneys.

The installation of an exhaust gas scrubber is associated with a large expansion of the gym at the expense of cargo space. Sometimes such modernization may prove unprofitable or impossible.

On the other hand, if a correct design is made and a feasible installation solution is found, scrubbers are a good way to reduce emissions from the ship, not only sulfur oxides but also soot. At the same time, it is possible to ensure the economic operation of the ship by avoiding the need for expensive types of fuel.

The costs of purchasing an exhaust gas desulfurization installation on a ship are high, in millions of EUR and this sum represents a significant share in the cost of the entire unit. In addition, waste generated in scrubber flue gas desulfurization processes is a significant problem.

If we count the costs of purchasing a desulfurization installation (scrubber) and add the operating costs of the installation, it may turn out that in the next 10 years it will be much more profitable to buy more expensive, desulfurized fuel. Despite these inconveniences, many ship-owners are opting for this type of solution.

As regards hybrid drive, it may be considered only on vessels operating short distances between ports that have infrastructure for charging batteries. In addition, the batteries take up valuable cargo space;

Besides as can be seen from the table on page 11, the cost of installing scrubbers is over 60% cheaper than modernization a ship onto a hybrid drive one.

4. Methodology of financial analysis

Costs in maritime transport are classified according to various criteria. One of them is the traditional division into own costs incurred by the enterprise in connection with the provision of transport services and external costs.
The methodology for classifying the shipping company's own costs is not internationally unified. Missing uniform standards causes difficulties in the analysis of costs in individual enterprises.

Generally, costs contain following categories:

- operating costs, which include expenses related to the day-to-day operation of ships; these are costs such as: crew costs, costs of materials and supplies necessary to provide the transport services, insurance costs;
- periodic maintenance costs that result from the need to maintain the seaworthiness of the ship (e.g. costs of class inspections and repairs);
- travel costs related to a specific journey and include such elements as: fuel costs, port fees, channel fees;
- capital costs result from the method of financing the ship, include depreciation, interest on loans, leasing installments;
- loading costs include loading, unloading and stowage costs,

The share of individual cost groups depends on such factors as the type of ship, size, age, flag, mode of operation. Determining the operating costs of a ship depends on the type of shipping services, the state of the ship's technology, management processes, maintenance, cargo and navigation planning as well as weather conditions.
Statistically, fuel costs appear to be the highest percentage of ship operating costs

- fuel - 50-80%,
- oils, greases - from 6%,
- crew costs - from 2%,
- auxiliary devices - from 2%,
- various fees - from 2%.

On the other hand, in the case of the bulk carrier it is estimated that the largest share has capital costs - about 42% and travel costs - about 40%.

From the other hand, when considering the cost structure of the passenger-car ferry, a high share of operating costs is visible. This is related to the relatively high crew costs, which results from the need to maintain a large number of hotel crew.

Given the dependence of costs on production volume, shipping costs are divided into:

- fixed costs that are incurred by the carrier regardless of the amount of freight carried and the route, include operating costs, periodic maintenance costs, capital costs;
- variable costs that relate to a specific transport service and include cruise costs (fuel, port fees), freight charges.

The organization of line services and constant service of a given route causes that the majority of costs, which in theory depend on the amount of transported load, are borne by the linear carrier on a permanent basis. A typical variable cost in liner shipping are freight costs. Cruise costs (fuel and port charges) are fixed costs for liner shipping. It is estimated that 80-90% of the costs incurred by carriers in regular shipping are fixed costs, irrespective of the amount of freight transported.

A characteristic feature of shipping is the close relationship between total costs and the size of sea-going ships - the unit cost decreases as load carrying capacity increases. For example, a ship with a size of 200 000 DWT[13] requires the same crew as a 20 000 ship DWT. Operating, fuel and capital costs increase disproportionately with unit growth, which causes unit costs to decline. Such cost formation causes a sustained tendency to build more and more transporters for bulk carriers, tankers and container ships.

Revenues in maritime transport. Cargo transportation is a service for which a fee is charged. The price formation mechanism in maritime transport is based on two methods - contractual prices and tariff prices.
In liner shipping a tariff system is used, which applies at a given time and on a given shipping line. The freight tariff is a set of rates that are quoted by line carriers along with the applicable collection rules. The level of rates depends primarily on the relationship between the demand for transport services and the supply of tonnage. In addition, their height is affected by the route, the load, its value and competition on the market. The rate refers to a specific amount of cargo, the so-called freight unit. A characteristic feature of the price system in liner shipping is the collection of

[13] DWT - Dead Weight Tonnage

additional fees by the carriers (freight additionals). They can be in the form of a quota or a percentage. They are used periodically or permanently.

Making a detailed analysis of the cost-effectiveness of using our hybrid electron accelerator system with a scrubber to purify the exhaust gas of marine diesel engines requires the preparation of an analysis for a specific ship based on systematically collected data from its operation.
Our analysis was made based on collected statistical data and has a simplified form aimed at selecting key parameters determining profitability and thus determining the directions and segments to which the product will be directed and outlining the economic goals that the future product will meet.

Basic calculations

The discounted cash flow method will be used to do the task.
The discounted cash flow method is based on discounting, i.e. reducing the expected net cash flow of investments for a given period to the present value - up to the beginning of the investment period, using the required rate of return on investment, i.e. the discount rate.

The discounted cash flow method will be used to implement the task.
The main parameters of the discount method:

- Net Present Value (**NPV**),
- Internal Rate of Return (**IRR**),
- Modified Internal Rate of Return (**MIRR**),
- Profitability index (**PI**),
- Discounted Payback Period (**DPP**).

Net Present Value - NPV

$$NPV = \sum_{t=1}^{n} \frac{R_t}{(1+i)^t}$$

where:
Rt = Net cash inflow outflows during a single period *t*
i = Discount rate or return that could be earned in alternative investments
t = Number of timer periods

A positive net present value indicates that the projected earnings generated by a project or investment - in present dollars - exceeds the anticipated costs, also in present dollars. It is assumed that an investment with a positive NPV will be profitable, and an investment with a negative NPV will result in a net loss.
This concept is the basis for the Net Present Value Rule, which dictates that only investments with positive NPV values should be considered.

NPV > 0 - the investment project is profitable, it can be accepted.
NPV = 0 - the investment project is neutral it can be accepted.
NPV < 0 - the investment is unprofitable it cannot be accepted.

Internal Rate of Return - IRR

The internal rate of return (IRR) is a metric used in capital budgeting to estimate the profitability of potential investments. The internal rate of return is a discount rate that makes the net present value (NPV) of all cash flows from a particular project equal to zero. It is important for a business to look at the IRR as the plan for future growth and expansion. The formula and calculation used to determine this figure follows.

$$0 = \mathrm{NPV} = \sum_{t=1}^{T} \frac{C_t}{(1+IRR)^t} - C_0$$

where:
Ct = Net cash inflow during the period t
C0 = Total initial investment costs
IRR = The internal rate of return
t = The number of time periods

To calculate IRR using the formula, one would set NPV equal to zero and solve for the discount rate (r), which is the IRR. Because of the nature of the formula, however, IRR cannot be calculated analytically and must instead be calculated either through trial-and-error or using software programmed to calculate IRR.

Modified Internal Rate of Return - MIRR.

The modified internal rate of return (MIRR) assumes that positive cash flows are reinvested at the firm's cost of capital and that the initial outlays are financed at the firm's financing cost. By contrast, the traditional internal rate of return (IRR) assumes the cash flows from a project are reinvested at the IRR itself. The MIRR, therefore, more accurately reflects the cost and profitability of a project.
Given the variables, the formula for MIRR is expressed as:

$$MIRR = \sqrt[n]{\frac{FV(\text{Positive cash flows} \times \text{Cost of capital})}{PV(\text{Initial outlays} \times \text{Financing cost})}} - 1$$

where:
FVCF(*c*)= the future value of positive cash flows at the cost of capital for the company
PVCF(*fc*)=the present value of negative cash flows at the financing cost of the company
n = number of periods

The MIRR is used to rank investments or projects of unequal size. The calculation is a solution to two major problems that exist with the popular IRR calculation. The first main problem with IRR is that multiple solutions can be found for the same project. The second problem is that the assumption that positive cash flows are reinvested at the IRR is considered impractical in practice. With the MIRR, only a single solution exists for a given project, and the reinvestment rate of positive cash flows is much more valid in practice.
The MIRR allows project managers to change the assumed rate of reinvested growth from stage to stage in a project. The most common method is to input the average estimated cost of capital, but there is flexibility to add any specific anticipated reinvestment rate.

Profitability Index - PI

The profitability index is an index that attempts to identify the relationship between the costs and benefits of a proposed project through the use of a ratio calculated as:

$$= \frac{\text{PV of Future Cash Flows}}{\text{Initial Investment}}$$

A profitability index of 1.0 is logically the lowest acceptable measure on the index, as any value lower than 1.0 would indicate that the project's present value (PV) is less

than the initial investment. As the value of the profitability index increases, so does the financial attractiveness of the proposed project.
Profitability index is an appraisal technique applied to potential capital outlays. The technique divides the projected capital inflow by the projected capital outflow to determine the profitability of a project. As indicated by the formula above, the profitability index uses the present value of future cash flows and the initial investment to represent the aforementioned variables.

Discounted Payback Period - DPP

The discounted payback period is a capital budgeting procedure used to determine the profitability of a project. A discounted payback period gives the number of years it takes to break even from undertaking the initial expenditure, by discounting future cash flows and recognizing the time value of money. The metric is used to evaluate the feasibility and profitability of a given project.
The more simplified *payback period* formula, which simply divides the total cash outlay for the project by the average annual cash flows, doesn't provide as accurate of an answer to the question of whether or not to take on a project because it assumes only one, upfront investment, and does not factor in the time value of money.

The general rule to consider when using the discounted payback period is to accept projects that have a payback period that is shorter than the target timeframe. A company can compare its required break-even date for a project to the point at which the project will break even according to the discounted cash flows used in the discounted payback period analysis, to approve or reject the project.

Break-even point (BEP)

Break-even analysis entails the calculation and examination of the margin of safety for an entity based on the revenues collected and associated costs. Analyzing different price levels relating to various levels of demand a business uses break-even analysis to determine what level of sales are necessary to cover the company's total fixed costs. A demand-side analysis would give a seller significant insight regarding selling capabilities.

Break-even analysis is useful in the determination of the level of production or a targeted desired sales mix. The study is for management's use only, as the metric and calculations are not necessary for external sources such as investors, regulators or financial institutions. This type of analysis depends on a calculation of BEP. The break-even point is calculated by dividing the total fixed costs of production by the price of a product per individual unit less the variable costs of production. Fixed costs are those which remain the same regardless of how many units are sold.

Break-even analysis looks at the level of fixed costs relative to the profit earned by each additional unit produced and sold. In general, a company with lower fixed costs will have a lower break-even point of sale. For example, a company with $0 of fixed costs will automatically have broken even upon the sale of the first product assuming variable costs do not exceed sales revenue. However, the accumulation of variable costs will limit the leverage of the company as these expenses come from each item sold.

Break-even analysis reveals the level of sales that must be achieved to generate a gross profit sufficient to cover overheads (fixed and variable) exceeding the break-even point.

Full assessment of the investment project's effectiveness must also include:

- Scenario analysis (scenario analysis should identify threats and weaknesses and lead to consideration of a pessimistic design variant).
- Sensitivity analysis (sensitivity analysis answers questions about the impact of specific risk factors on project profitability).

Tools:

The analysis will use the **Invest for Excel program of Datapartner Oy** from Finland.

Invest for Excel serves managers, investment analysts, controllers, investors as well as production, engineering and marketing teams, among others in the areas of: business planning, modeling of cash flows for projects, cost-benefit analysis.

5. Fuel as a basis for financial analysis

The hybrid electron accelerator system together with the scrubber for exhaust gas cleaning of marine diesel engines still requires a number of tests, in particular real-world tests.

At present, it is difficult to precisely determine all parameters, especially the costs related to the operation of the system, which is why a number of assumptions have been made in the presented calculations.

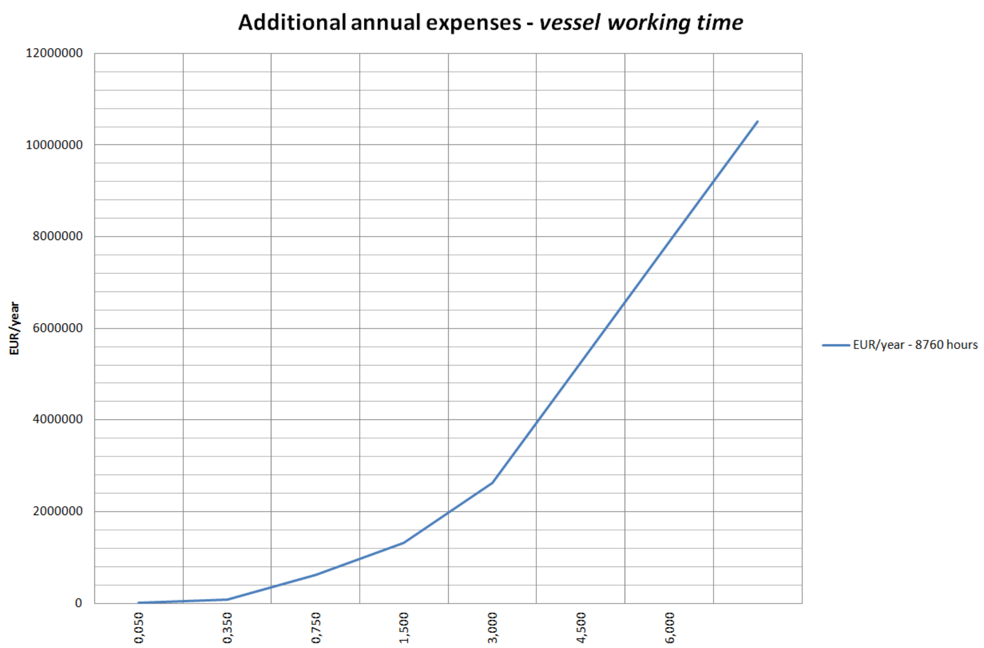
Benefits associated with the use of EB hybrid technology. Additional benefits arise from the difference in the purchase price of high and low sulfur fuel, because the use of hybrid EB exhaust gas cleaning technology allows the use of cheaper fuel with a higher sulfur content.

The basis for assessing the profitability of installing the system was the cost of using low sulfur fuel in exchange for cheaper high sulfur fuel.

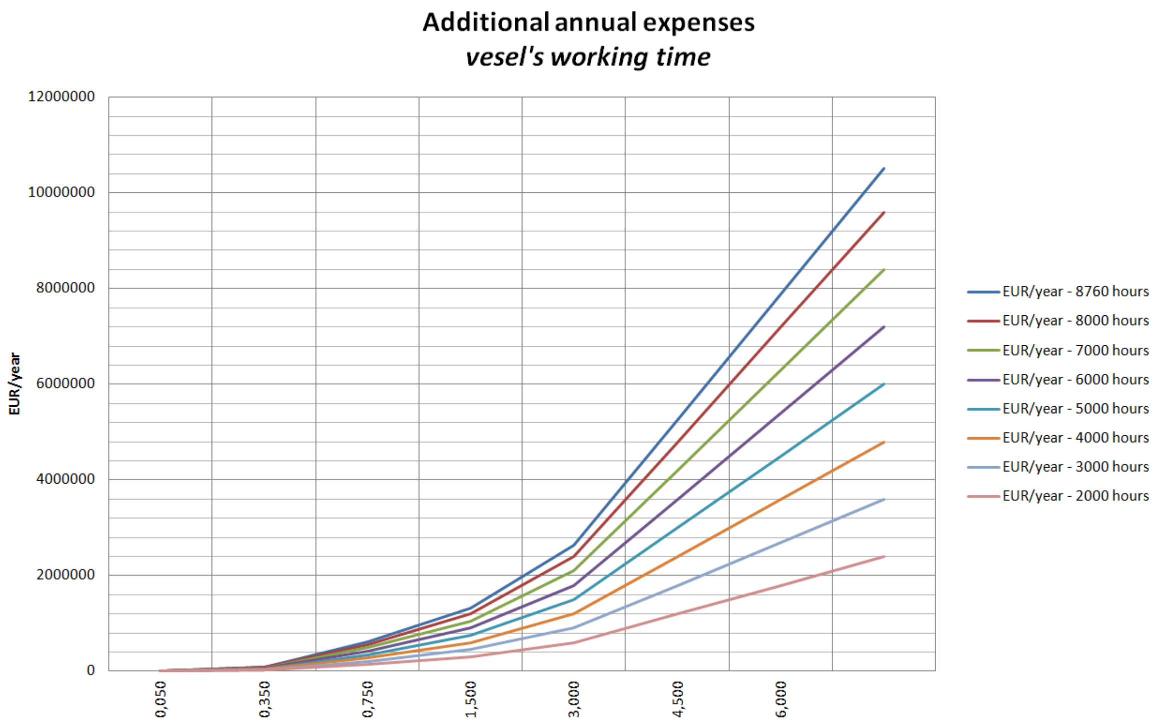
The stable difference in prices of these fuels over the past few years has remained stable at around 200 EUR per ton of fuel.

The calculation of the value of additional expenses related to the change of fuel used depends on the size of the ship, and basically the size and type of the marine engine used.

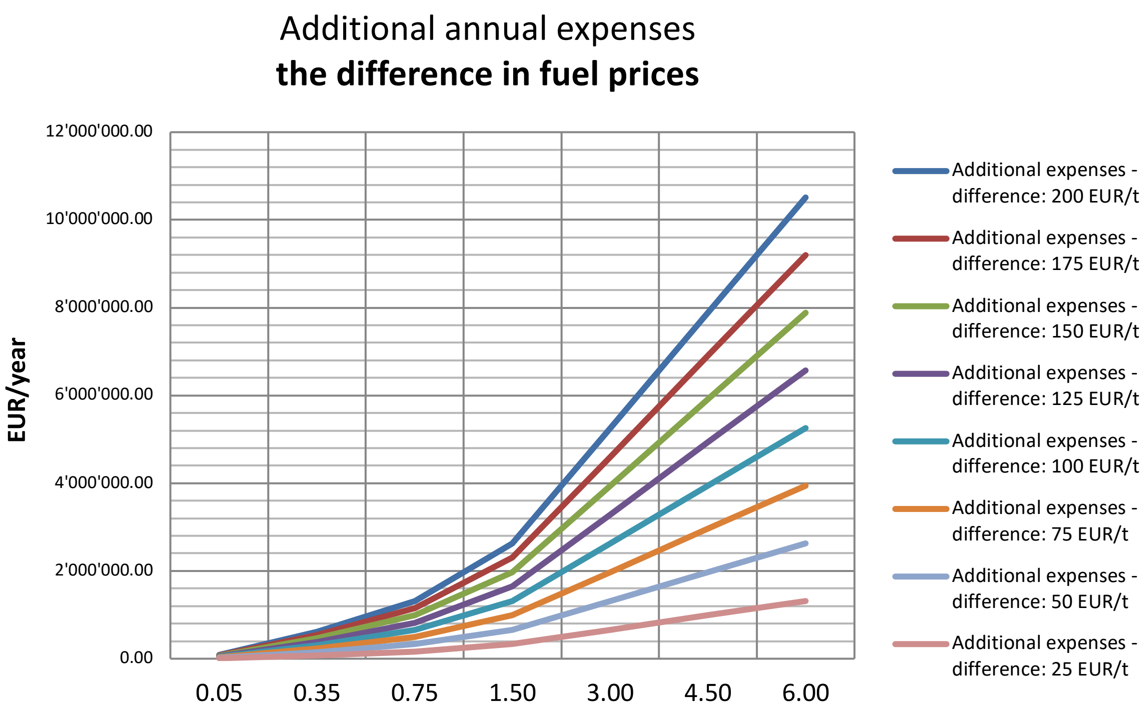
The chart below illustrates the value of additional expenses depending on the size of the engine measured by the specific fuel consumption.



Significant differences in the value of additional expenses occur depending on the amount of effective movement time of the ship. The differences are illustrated in the chart below.



The chart below shows the change in additional annual expenses depending on the value of the difference between the price of low and high sulfur fuel.



The presented analysis clearly indicates that the introduction of low-sulfur fuel generates high costs, especially for large ships sailing long in limited emission zones. The difference in the prices of high and low sulfur fuel has a great impact on the amount of additional annual expenses when changing fuel.

6. Main parameters adopted in calculation

In order to evaluate an investment project, it is necessary to calculate basic economic indicators such as NPV, IRR, PI, etc.
The calculation of ratios requires the development of a profit and loss account, balance sheet and cash flow statement forecast for the adopted calculation period. On the basis of the calculated present value of cash flows (PV) for a properly determined discount rate, the present value of net NPVs is calculated.

Calculations of the profitability of the application of hybrid EB technology for cleaning exhaust gases emitted by marine engines required determining the following parameters:

BASIC PARAMETERS

Calculation period - a 10-year period was assumed, assuming that ships already in service can be modernized and the profitability for a relatively short product life should be checked.

Currency - EUR was used in the calculations

Discount rate - the discount rate was adopted on the basis of WACC[14] calculations based on the adopted cost of foreign capital, expected return on equity, tax rate and the share of equity and foreign capital

Income tax - a 20% tax rate was adopted (EU average)

INVESTMENT

Investment value - for the analysis of investment profitability for the end customer, the investment value corresponds to the sale price of the installation including assembly on the ship. In the case of cost-effectiveness analysis from the manufacturer's and installer's point of view, it was assumed that no additional investment outlays would be required.

Depreciation - a depreciation level of 10% was implemented

HAZARD AND LOSS ACCOUNT

INCOME

Additional expenses related to the change of fuel - the basis for assessing the profitability of installing the system was the cost of using low-sulfur fuel in exchange for cheaper high sulfur fuel.

Number of operating hours - time in the sailing hours in the controlled emission area

Specific fuel consumption - the amount of fuel burned per hour.

Engine power - analysis performed for medium-sized seagoing ships

Power obtained from a unit of fuel - data obtained from many sources indicate large differences in values

Difference in fuel prices - difference estimated on the basis of an analysis of fuel prices in the port of Rotterdam.

[14] WACC - Weighted Average Cost of Capital

VARIABLE COSTS

Accelerator and scrubber supply costs - the largest costs associated with securing the power supply of the fast electron accelerator and energy supplying the scrubber system.

Unit price of fuel - the price of fuel based on low sulfur fuel

Amount of fuel consumed by the generator - data collected from sources available from generator manufacturers

Unit fuel consumption generator - data collected from sources available from generator manufacturers

Accelerator and scrubber power - prognostic data requiring confirmation

Energy demand indicator - prognostic data requiring confirmation

Costs of other consumables - basis for calculation - fuel value and consumables cost index - prognostic data requiring confirmation

Service costs - estimation base - investment value and service cost index

Other variable costs - calculation basis - fuel value and consumables cost index - prognostic data requiring confirmation

FIXED COSTS

Personnel costs - calculated on the basis of employment forecasts for employees in the marketing area, monthly rate and number of months.

Other fixed costs - forecast based on 5% of the investment value

FINANCIAL COSTS

Interest on the loan - forecast

7. Analysis of investment profitability for the target customer

Profitability calculations for the application of hybrid EB technology for cleaning exhaust gases emitted by marine engines were made assuming the following values of the basic parameters specified for the three variants:

- OPTIMAL,
- OPTIMISTIC
- PESSIMISTIC

The scenario analysis was carried out to check the economic impact of changes in the set of main parameters used to calculate financial effects. The implemented parameter values are presented in the table on page 27. This is important because the available data is characterized by a wide range in the values of these parameters.

For example, fuel prices in 2019 fluctuated by almost 150 USD, but long-term trends in fuel prices indicate that for many years the difference in the price of high-sulfur and low-sulfur fuels has remained at the same level of approx. 200 EUR / t.

Our analysis checks what economic effect will be obtained in the event of overlapping of particularly adverse events. For the purposes of the analysis, we have created 3 variants in which we adopted extreme values.
In the **optimistic variant**, we assumed that all variables will have extremely favorable values, while in the **pessimistic variant**, they will be extremely negative.

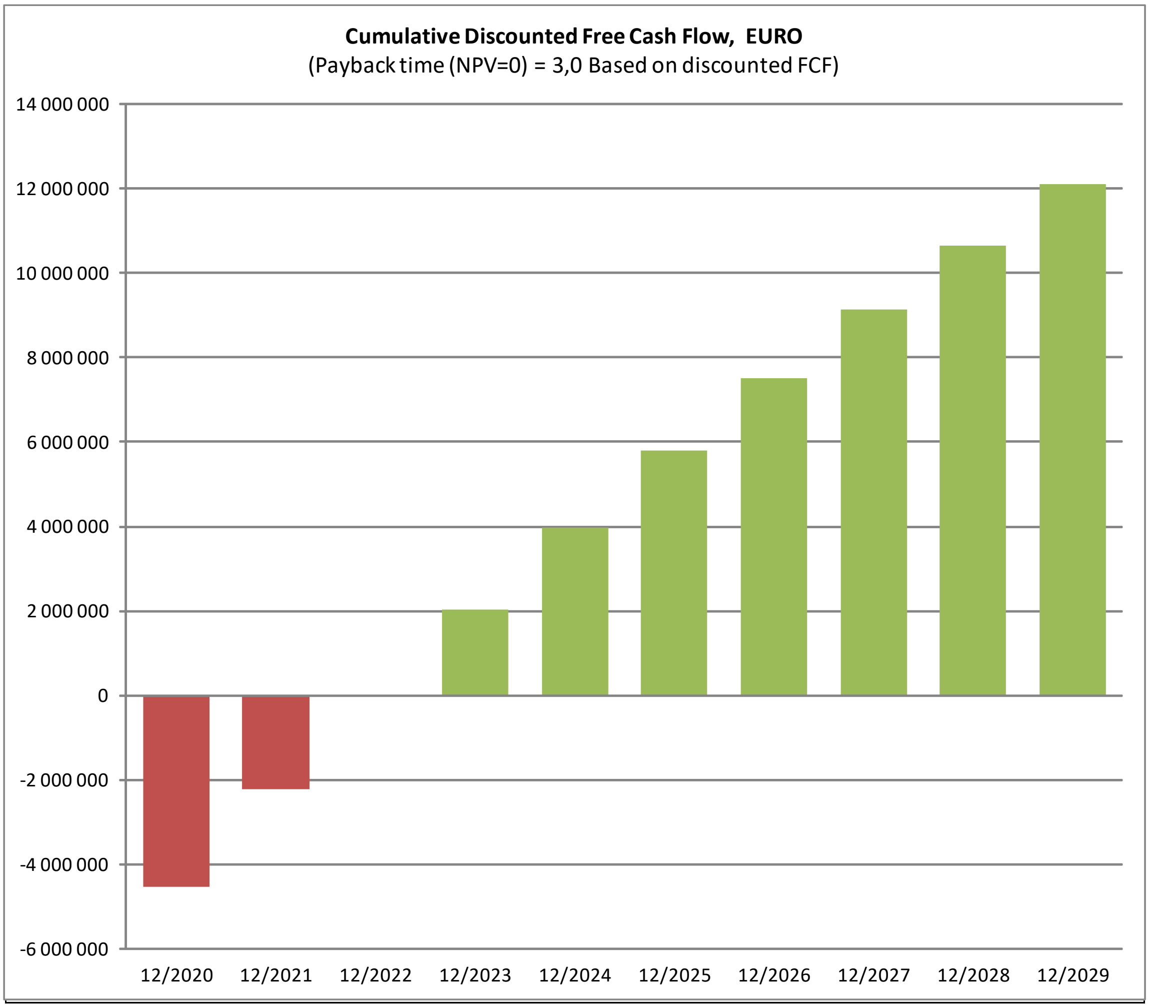
Parameters in the scenario analisys

Description	IU	Parameter value for the specified option		
		Optimal	Optymistic	Pesimistic
Discount rate	%	6,20	6,00	8,00
Investment value	EUR	7 000 000	5 000 000	8 000 000
Working hours of the vessel	h	7 000	7 500	5 000
Unit fuel consumption	t/h	4,00	8,00	2,96
Engine power	kW	40 000	40 000	40 000
Power from the fuel unit	kg/kWh	0,100	0,200	0,074
Difference in fuel price	EUR/t	200,00	220,00	180,00
LSMGO	EUR/t	555,00	570,00	530,00
IFO380	EUR/t	355,00	350,00	350,00
Power costs of accelerator and scrubber				
Fuel unit price	EUR/t	555,00	570,00	530,00
Fuel consumption of the generator	t/year	1 176	720	1 280
Unit fuel consumption of the generator	kg/kWh	0,14	0,12	0,16
Accelerator and scrubber total power	kW	1 200	800	1 600
Energy demand indicator	%	3,00%	2,00%	4,00%
Costs of other consumables	EUR	310 800,00	342 000,00	235 320,00
Calculation base - fuel value	EUR	15 540 000,00	34 200 000,00	7 844 000,00
Consumables costs indicator	%	2%	1%	3%
Service costs	EUR	350 000	200 000	480 000
Investment value	EUR	7 000 000	5 000 000	8 000 000
Service costs indicator	%	5%	4%	6%
Other variable costs	EUR	621 600,00	1 026 000,00	392 200,00
Other variable costs	EUR	15 540 000,00	34 200 000,00	7 844 000,00
Other variable costs indicator	%	4%	3%	5%
FIXED COSTS				
Personnel costs	EUR	216 000,00	120 000,00	336 000,00
Number of employees	employees	3	2	4
Monthly rate	EUR/month	6000	5000	7000
Number of months	months	12	12	12
Other fixed costs	EUR	350 000,00	250 000,00	400 000,00
Interest on loan				
Interest rate	%	7%	6%	8%

For the Optimal Variant, the results are presented below (details in Annex 1):

BASIC VALUES					
Project description	**Optimal option - customer**				
Calculation term, years	10 years				
Interval length, months	12				
Number of intervals	10		10		
	(MM/YYYY)				
Calculation term begins	01/2020	(in the beginning of period)			
Calculation point	01/2020	(in the beginning of period)			
Calculation term ends	12/2029	(in the end of the period)			
Figures (1/1000/1000000)	**1**				
Currency	**EURO**				
Discount rate (per annum)	**6,20**	% (required rate of return)			
	2020	2021	2022	2023	2024 ->
Income tax %	**20**	**20**	**20**	**20**	**20**

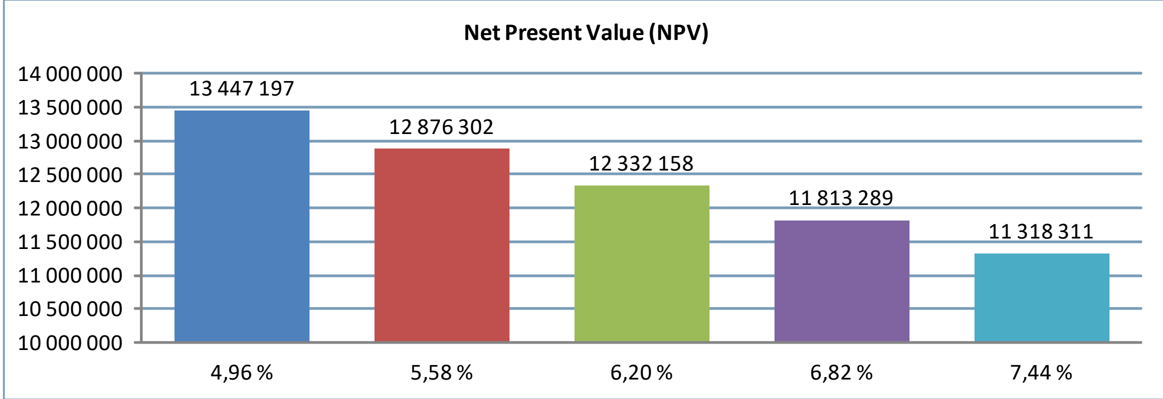
PROFITABILITY ANALYSIS						
	Project description	**Optimal option - customer**				EURO
	Nominal value of all investments		7 000 000	Discounted investments		6 591 337
	Required rate of return		6,20 %			
	Calculation term		10,0	years		1/2020 - 12/2029
	Calculation point		1/2020	(In the beginning of period)		
	Present value of business cash flows	Nominal	PV	Notes		
±	PV of operative cash flow		18 683 759			
+	PV of residual value		239 736			
	Present value of business cash flows		**18 923 495**			
-	Present value of reinvestments	0	0			
	Total Present Value (PV)		**18 923 495**			
	Investment proposal	Nominal	PV			
-	Proposed investments in assets	-7 000 000	-6 591 337			
+	Investment subventions	0	0			
	Investment proposal	-7 000 000	-6 591 337			
	Net Present Value (NPV)		**12 332 158**	>= 0	->	profitable
	NPV as a monthly annuity		137 101			
	Internal Rate of Return (IRR)		53,30%	>= 6,2 %	->	profitable
	Modified Internal Rate of Return (MIRR)		21,10%	>= 6,2 %	->	profitable
	Profitability Index (PI)		2,87	>= 1	->	profitable
	Payback time, years		3,0	Based on discounted FCF		
	Return on net assets (RONA), %		94,5 %	Average 10 years		
	Economic Value Added (EVA)		1 689 781	Average 10 years		
	Discounted Value Added (DCVA)		12 076 598			
	Internal Rate of Return based on DCVA (IRRd)		37,88%	>= 6,2 %	->	profitable
	Modified Internal Rate of Return based on DCVA (MIRRd)		26,03%	>= 6,2 %	->	profitable
	Payback time, years, based on DCVA		0,0			
	Cumulative discounted value added 1/2020->1/2020		0			
	Cumulative discounted value added 1/2020->12/2020		1 473 080			
	Calculation point, Payback		1/2020			
	Calculation is made by	ANDRZEJ PRYZOWICZ				2019-09-28
	Calculation file	H:\AKTUALNE 2019\BIOPOLINEX AP\BIOPOLINEX_PROJEKTY\PROJEKT ARIES\REALIZACJA\ANALIZA UZYTKOWNIK SYSYTEMU_40MW_WARIANT 1_ENG.xlsm				



Discounted FCF (Discounted Cash Flow) - is a valuation method used to estimate the value of an investment based on its future cash flows. DCF analysis attempts to figure out the value of a company today, based on projections of how much money it will generate in the future.

Discount factor's impact on profitability

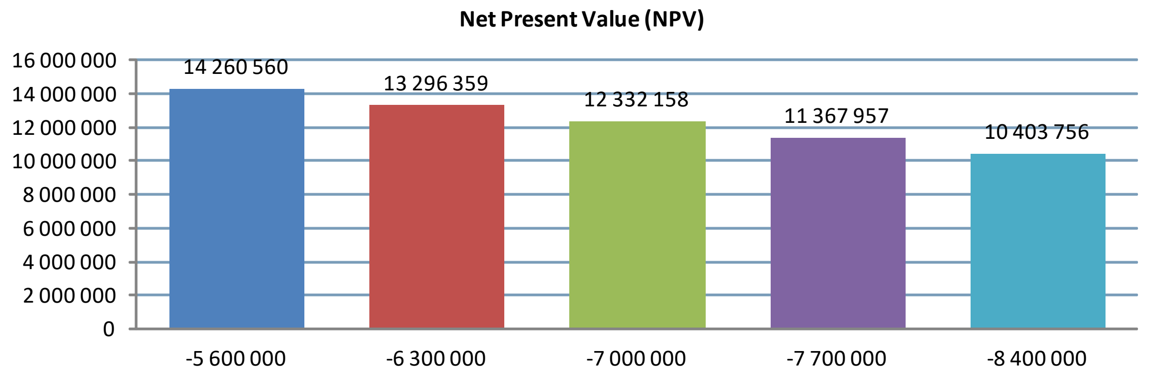
Discount factor	4,96 %	5,58 %	6,20 %	6,82 %	7,44 %
Change, %	-20,0 %	-10,0 %	0,0 %	+10,0 %	+20,0 %
Net Present Value (NPV)	13 447 197	12 876 302	12 332 158	11 813 289	11 318 311
Change, %	+9,0 %	+4,4 %	0,0 %	-4,2 %	-8,2 %



Key financials	4,96 %	5,58 %	6,20 %	6,82 %	7,44 %
EBITDA; Operating income before depreciation, EURO	3 098 920	3 098 920	3 098 920	3 098 920	3 098 920
EBITDA, %	55,3%	55,3%	55,3%	55,3%	55,3%
EBIT; Operating income, EURO	2 398 920	2 398 920	2 398 920	2 398 920	2 398 920
EBIT, %	42,8%	42,8%	42,8%	42,8%	42,8%
Return on net assets (RONA), %	35,61%	35,61%	35,61%	35,61%	35,61%
Economic Value Added (EVA), EURO	1 647 956	1 606 184	1 564 411	1 522 639	1 480 866

Total investment's impact on profitability

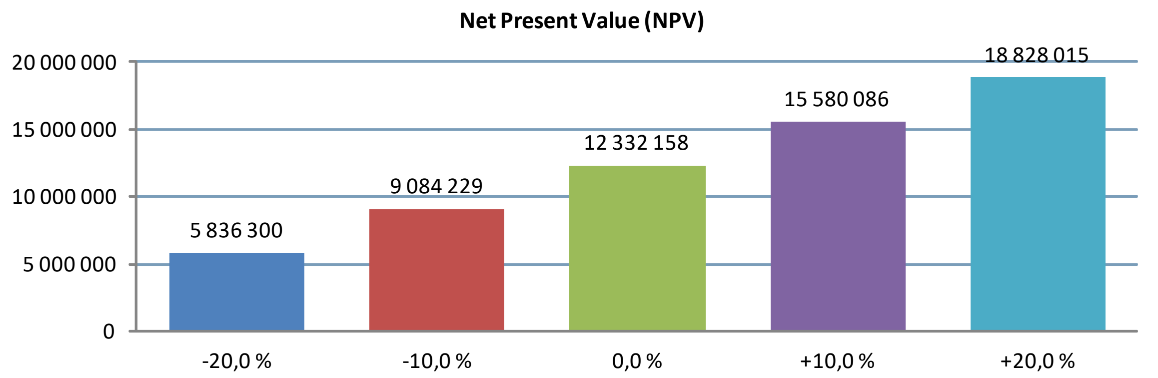
Total investment, EURO	-5 600 000	-6 300 000	-7 000 000	-7 700 000	-8 400 000
Change, %	-20,0 %	-10,0 %	0,0 %	+10,0 %	+20,0 %
Net Present Value (NPV)	14 260 560	13 296 359	12 332 158	11 367 957	10 403 756
Change, %	+15,6 %	+7,8 %	0,0 %	-7,8 %	-15,6 %



Key financials 12/2020	-5 600 000	-6 300 000	-7 000 000	-7 700 000	-8 400 000
EBITDA; Operating income before depreciation, EURO	3 238 920	3 168 920	3 098 920	3 028 920	2 958 920
EBITDA, %	57,8%	56,6%	55,3%	54,1%	52,8%
EBIT; Operating income, EURO	2 678 920	2 538 920	2 398 920	2 258 920	2 118 920
EBIT, %	47,8%	45,3%	42,8%	40,3%	37,8%
Return on net assets (RONA), %	48,86%	41,55%	35,61%	30,67%	26,51%
Economic Value Added (EVA), EURO	1 866 169	1 715 290	1 564 411	1 413 532	1 262 653

Income's impact on profitability

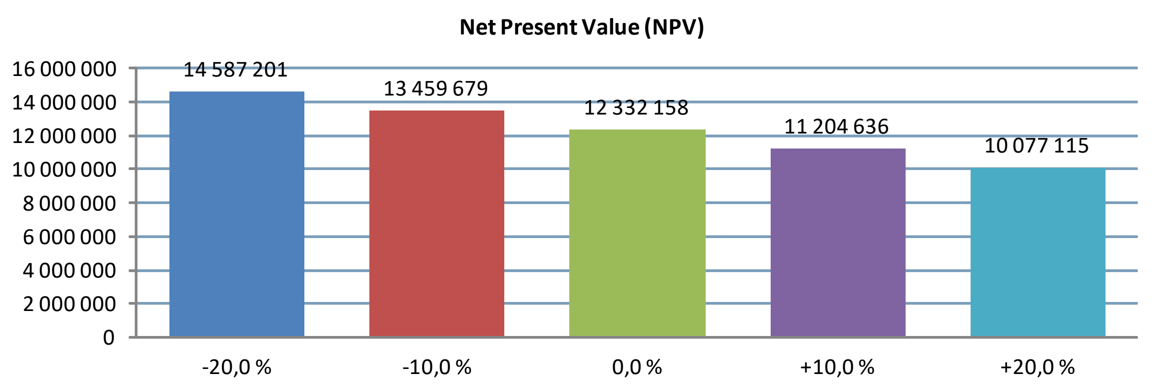
Change in Income, %	-20,0 %	-10,0 %	0,0 %	+10,0 %	+20,0 %
Net Present Value (NPV)	5 836 300	9 084 229	12 332 158	15 580 086	18 828 015
Change, %	-52,7 %	-26,3 %	0,0 %	+26,3 %	+52,7 %



Key financials 12/2020	-20,00%	-10,00%	0,00%	+10,00%	+20,00%
EBITDA; Operating income before depreciation, EURO	1 978 920	2 538 920	3 098 920	3 658 920	4 218 920
EBITDA, %	44,2%	50,4%	55,3%	59,4%	62,8%
EBIT; Operating income, EURO	1 278 920	1 838 920	2 398 920	2 958 920	3 518 920
EBIT, %	28,5%	36,5%	42,8%	48,0%	52,4%
Return on net assets (RONA), %	19,25%	27,48%	35,61%	43,62%	51,52%
Economic Value Added (EVA), EURO	674 198	1 119 304	1 564 411	2 009 518	2 454 624

Variable cost's impact on profitability

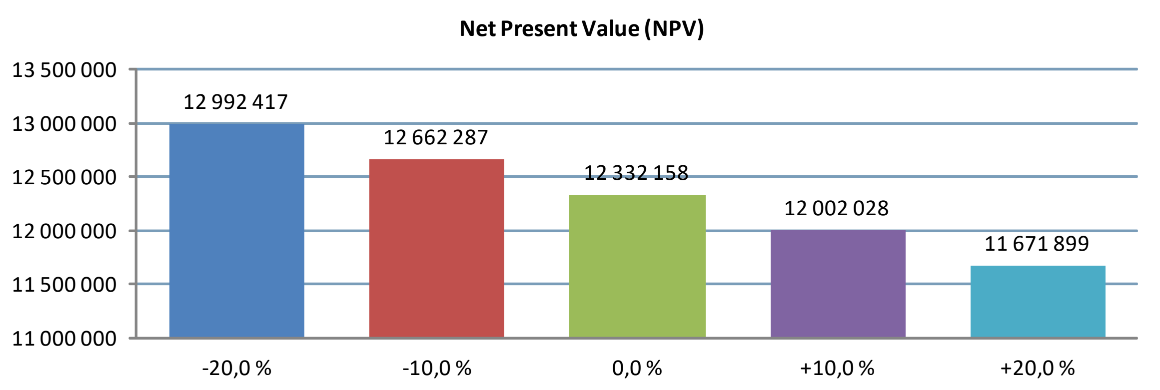
Change in Variable costs, %	-20,0 %	-10,0 %	0,0 %	+10,0 %	+20,0 %
Net Present Value (NPV)	14 587 201	13 459 679	12 332 158	11 204 636	10 077 115
Change, %	+18,3 %	+9,1 %	0,0 %	-9,1 %	-18,3 %



Key financials 12/2020	-20,0 %	-10,0 %	0,0 %	+10,0 %	+20,0 %
EBITDA; Operating income before depreciation, EURO	3 485 936	3 292 428	3 098 920	2 905 412	2 711 904
EBITDA, %	62,2%	58,8%	55,3%	51,9%	48,4%
EBIT; Operating income, EURO	2 785 936	2 592 428	2 398 920	2 205 412	2 011 904
EBIT, %	49,7%	46,3%	42,8%	39,4%	35,9%
Return on net assets (RONA), %	41,31%	38,46%	35,61%	32,75%	29,89%
Economic Value Added (EVA), EURO	1 873 662	1 719 037	1 564 411	1 409 785	1 255 160

Fixed cost's impact on profitability

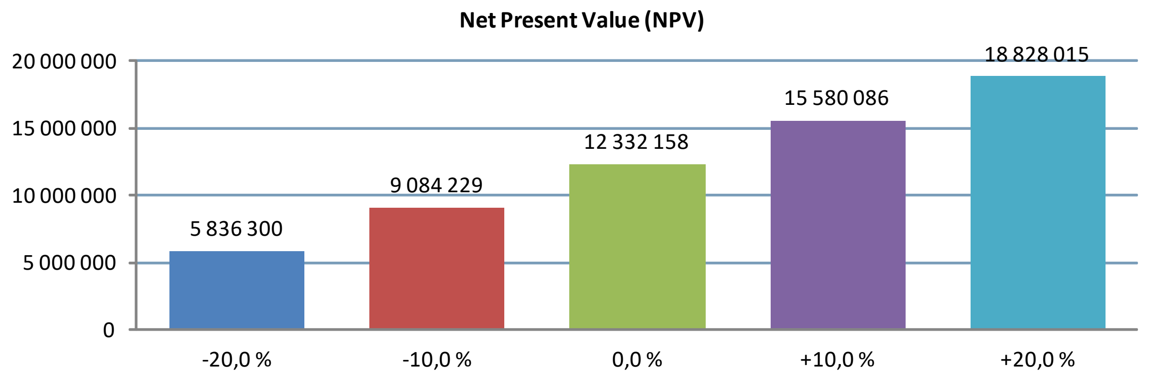
Change in Fixed costs, %	-20,0 %	-10,0 %	0,0 %	+10,0 %	+20,0 %
Net Present Value (NPV)	12 992 417	12 662 287	12 332 158	12 002 028	11 671 899
Change, %	+5,4 %	+2,7 %	0,0 %	-2,7 %	-5,4 %



Key financials 12/2020	-20,0 %	-10,0 %	0,0 %	+10,0 %	+20,0 %
EBITDA; Operating income before depreciation, EURO	3 212 120	3 155 520	3 098 920	3 042 320	2 985 720
EBITDA, %	57,4%	56,3%	55,3%	54,3%	53,3%
EBIT; Operating income, EURO	2 512 120	2 455 520	2 398 920	2 342 320	2 285 720
EBIT, %	44,9%	43,8%	42,8%	41,8%	40,8%
Return on net assets (RONA), %	37,29%	36,45%	35,61%	34,77%	33,93%
Economic Value Added (EVA), EURO	1 654 971	1 609 691	1 564 411	1 519 131	1 473 851

Variable´s impact on profitability

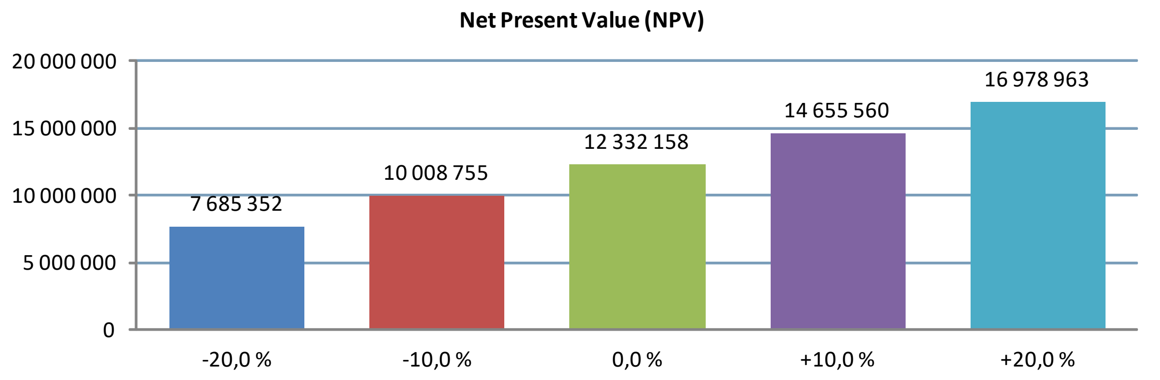
Variable	(449) * Difference in fuel price				
Change in value, %	**-20,0 %**	**-10,0 %**	**0,0 %**	**+10,0 %**	**+20,0 %**
Sample value	160,0	180,0	200,0	220,0	240,0
Net Present Value (NPV)	5 836 300	9 084 229	12 332 158	15 580 086	18 828 015
Change, %	-52,7 %	-26,3 %	0,0 %	+26,3 %	+52,7 %



Key financials 12/2020	**-20,0 %**	**-10,0 %**	**0,0 %**	**+10,0 %**	**+20,0 %**
EBITDA; Operating income before depreciation, EURO	1 978 920	2 538 920	3 098 920	3 658 920	4 218 920
EBITDA, %	44,2%	50,4%	55,3%	59,4%	62,8%
EBIT; Operating income, EURO	1 278 920	1 838 920	2 398 920	2 958 920	3 518 920
EBIT, %	28,5%	36,5%	42,8%	48,0%	52,4%
Return on net assets (RONA), %	19,25%	27,48%	35,61%	43,62%	51,52%
Economic Value Added (EVA), EURO	674 198	1 119 304	1 564 411	2 009 518	2 454 624

Variable´s impact on profitability 2

Variable	(447) Engine power				
Change in value, %	**-20,0 %**	**-10,0 %**	**0,0 %**	**+10,0 %**	**+20,0 %**
Sample value	32 000,0	36 000,0	40 000,0	44 000,0	48 000,0
Net Present Value (NPV)	7 685 352	10 008 755	12 332 158	14 655 560	16 978 963
Change, %	-37,7 %	-18,8 %	0,0 %	+18,8 %	+37,7 %



Key financials 12/2020	**-20,0 %**	**-10,0 %**	**0,0 %**	**+10,0 %**	**+20,0 %**
EBITDA; Operating income before depreciation, EURO	2 295 936	2 697 428	3 098 920	3 500 412	3 901 904
EBITDA, %	51,2%	53,5%	55,3%	56,8%	58,1%
EBIT; Operating income, EURO	1 595 936	1 997 428	2 398 920	2 800 412	3 201 904
EBIT, %	35,6%	39,6%	42,8%	45,5%	47,6%
Return on net assets (RONA), %	24,02%	29,85%	35,61%	41,28%	46,87%
Economic Value Added (EVA), EURO	927 810	1 246 111	1 564 411	1 882 711	2 201 012

Parameters in the break-even analysis

Description	IU	Parameter value for the specified option	
		Optimal	Break-even point
Discount rate	%	6,2%	53,3%
Investment value	EUR	7 000 000	15 953 019
Working hours of the vessel	h	7 000	3 285
Unit fuel consumption	t/h	4,00	2,18
Engine power	kW	40 000	18 769
Power from the fuel unit	kg/kWh	0,100	0,054
Difference in fuel price	EUR/t	200,00	115,00
LSMGO	EUR/t	555,00	470,00
IFO380	EUR/t	355,00	431,00
Power costs of accelerator and scrubber			
Fuel unit price	EUR/t	555,00	555,00
Fuel consumption of the generator	t/year	1 176	4 986
Unit fuel consumption of the generator	kg/kWh	0,14	0,59
Accelerator and scrubber total power	kW	1 200	5 407
Energy demand indicator	%	3,00%	12,70%
Consumables costs indicator	%	2,0%	15,6%
Service costs indicator	%	5,0%	35,4%
Other variable costs indicator	%	4,0%	17,6%
Number of employees	employees	3	32,00
Monthly rate	EUR/month	6 000	64 731,00

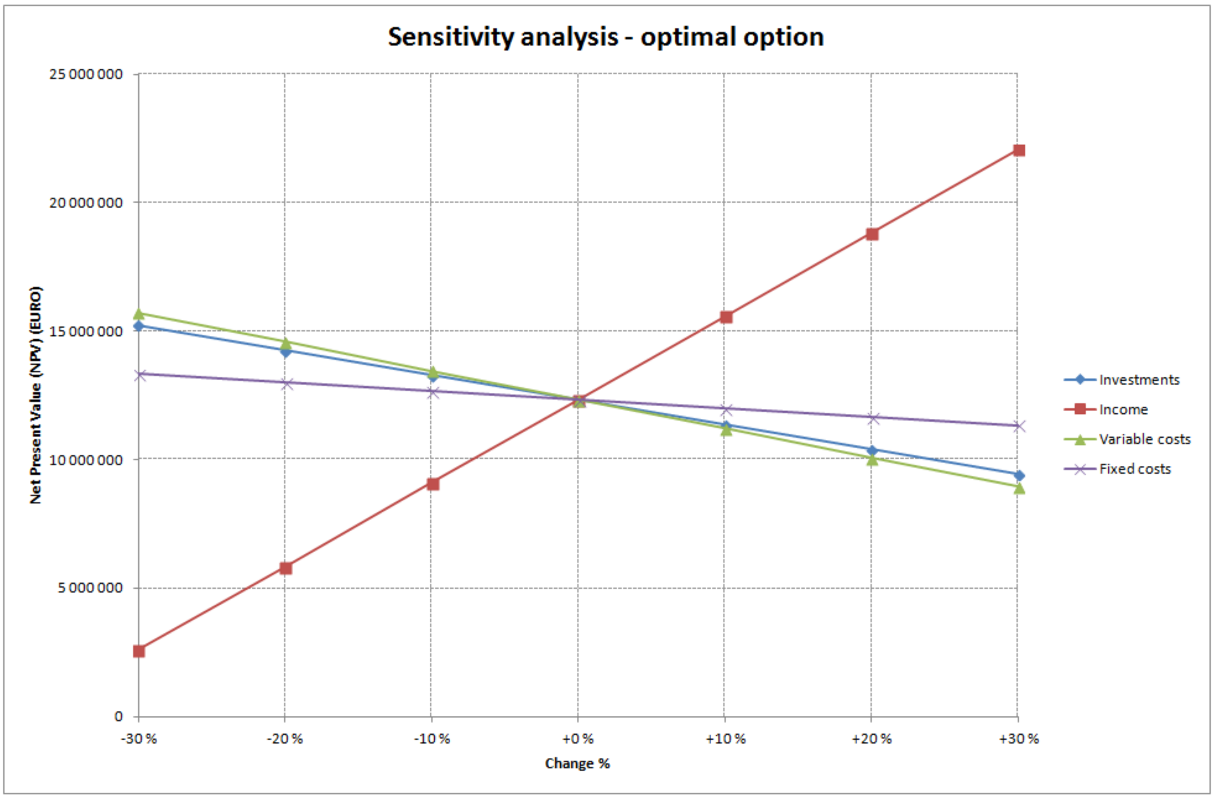
Taking into account the risk associated with the project - scenario analysis

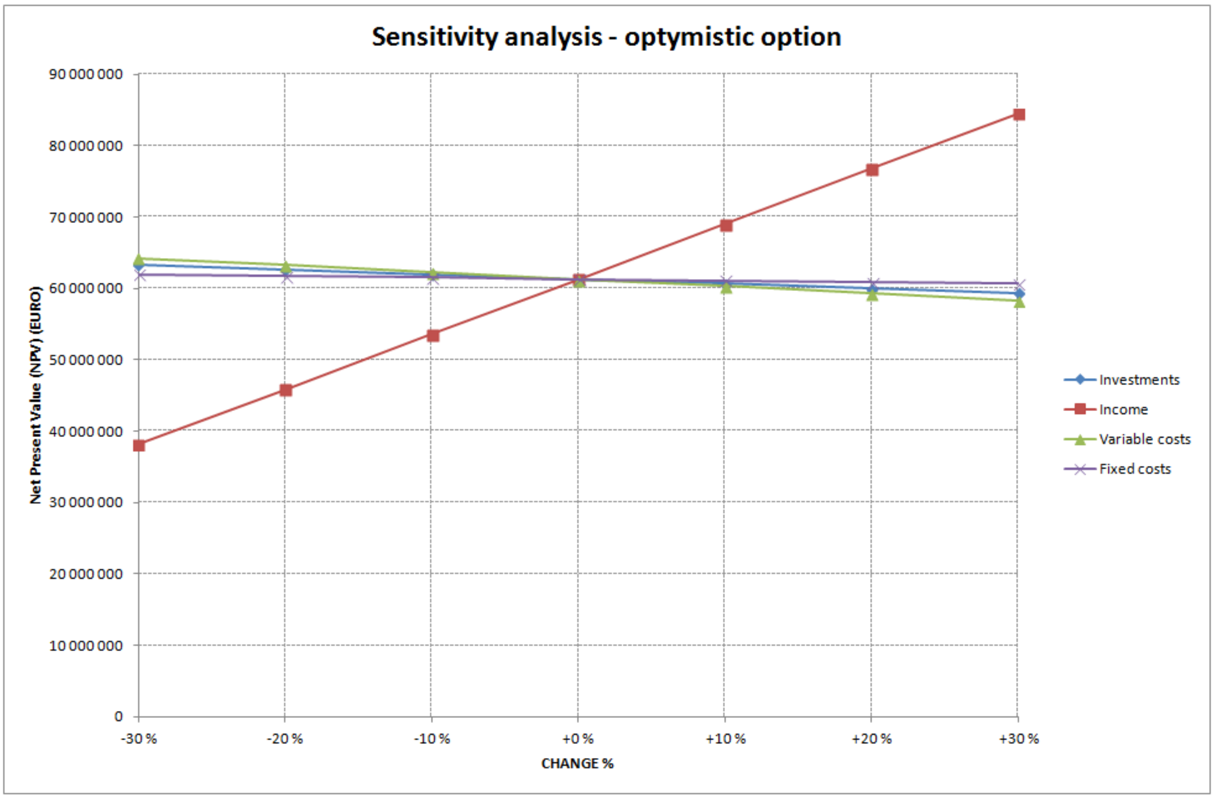
PROFITABILITY COMPARISON			
Figures	EURO	EURO	EURO
Project description	**Optimal option - customer**	**Optymistic option - customer**	**Pesimistic option - customer**
Nominal value of all investments	**7 000 000**	**5 000 000**	**8 000 000**
Required rate of return	**6,20%**	**6,00%**	**8,00%**
Calculation term (years)	**10,0**	**10,0**	**10,0**
Calculation term	1/2020 - 12/2029	1/2020 - 12/2029	1/2020 - 12/2029
Calculation point	1/2020	1/2020	1/2020
Interval length (months)	12	12	12
PV of operative cash flow	18 683 759	65 410 722	1 106 934
PV of residual value	239 736	604 928	84 301
Present value of business cash flows	18 923 495	66 015 650	1 191 235
Present value of reinvestments	0	0	0
Total Present Value (PV)	**18 923 495**	**66 015 650**	**1 191 235**
Proposed investments in assets	-6 591 337	-4 716 981	-7 407 407
Investment subventions	0	0	0
Investment proposal	-6 591 337	-4 716 981	-7 407 407
Net Present Value (NPV)	**12 332 158**	**61 298 668**	**-6 216 172**
NPV as a monthly annuity	137 101	675 659	-74 506
Internal Rate of Return (IRR)	53,30%	-	-20,75%
Modified Internal Rate of Return (MIRR)	21,10%	-	-10,09%
Profitability Index (PI)	2,87	14,00	0,16
Payback time, years	3,0	0,0	-
Calculation point, Payback	1/2020	1/2020	1/2020
Return on net assets (RONA), %	94,49%	366,85%	-26,50%
Economic Value Added (EVA)	1 689 781	8 323 380	-941 280
Discounted Value Added (DCVA)	12 076 598	61 078 881	-6 577 894
Internal Rate of Return based on DCVA (IRRd)	37,88%	32,10%	32,10%
Modified Internal Rate of Return based on DCVA (MIRRd)	26,03%	21,38%	21,38%
Payback time, years, based on DCVA	0,0	0,0	-
Calculation is made by	ANDRZEJ PRYZOWICZ	ANDRZEJ PRYZOWICZ	ANDRZEJ PRYZOWICZ
Date	2019-09-28	2019-09-28	2019-09-28
Comment			

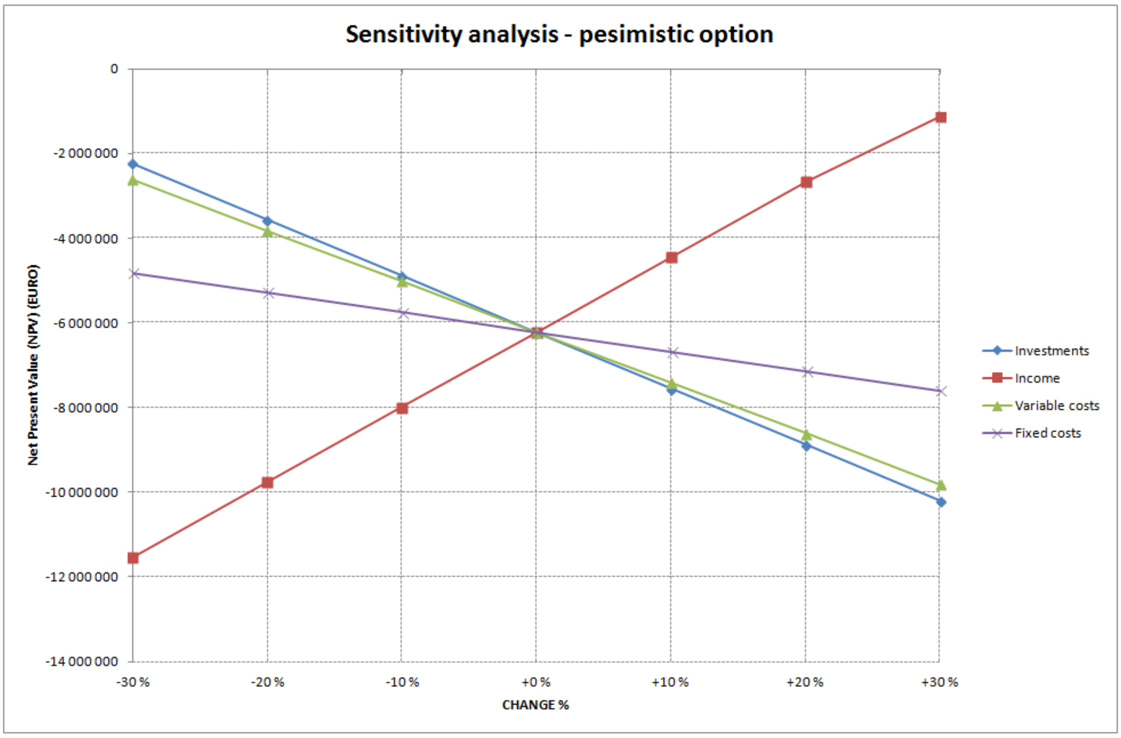
DCVA - Discounted Value Added

For a more complete assessment, a sensitivity analysis ("what if analysis") was also carried out. Such analysis is a process consisting in measuring the impact that changes in individual variables or their combinations have on the level of profit achieved by an entity.

The main task of sensitivity analysis is to calculate a turning point, which means bringing the cost of the product sold into line with income.


Sensitivity analysis - optimal option
Net Present Value (NPV) (EURO)
25 000 000
20 000 000
15 000 000
10 000 000
5 000 000
0
-30 %
-20 %
-10 %
+0 %
+10 %
+20 %
+30 %
Change %
Investments
Income
Variable costs
Fixed costs


Sensitivity analysis - optymistic option
Net Present Value (NPV) (EURO)
90 000 000
80 000 000
70 000 000
60 000 000
50 000 000
40 000 000
30 000 000
20 000 000
10 000 000
0
-30 %
-20 %
-10 %
+0 %
+10 %
+20 %
+30 %
CHANGE %
Investments
Income
Variable costs
Fixed costs



In each of the variants, the most sensitive parameter is the level of revenue. The value of investments and the level of variable costs are very sensitive, but only for the pessimistic variant.

8. Analysis of investment profitability for contractors and installation manufacturers

As in the case of profitability calculations for the end customer, profitability analysis for the production and sale of hybrid EB technology installations was carried out. The following values of basic parameters adopted for the three

- OPTIMAL,
- OPTIMISTIC,
- PESSIMISTIC

variants were implemented:

Parameters in the scenario analisys				
Description	IU	Parameter value for the specified option		
		Optimal	Optymistic	Pesimistic
Discount rate	%	6,50	5,00	8,00
Investment value	EURO	0	0	0
Quantity of systems sold	pcs	111	191	63
Price	EURO/pcs	7 000 000,00	8 000 000,00	5 000 000,00
The value of sales	EURO			
Cost of materials indicator	%	50%	47%	54%
The value of sales	EURO			
Staff variable costs indicator	%	15%	12%	17%
The value of sales	EURO			
Other variable costs indicator	%	5%	3%	7%
Number of employees	employees	167	191	189
Monthly rate	EUR/month	6 000,00	5 000,00	7 000,00
Number of months	months	12,00	12,00	12,00
The value of sales	EURO			
Other fixed costs indicator	%	10%	8%	12%

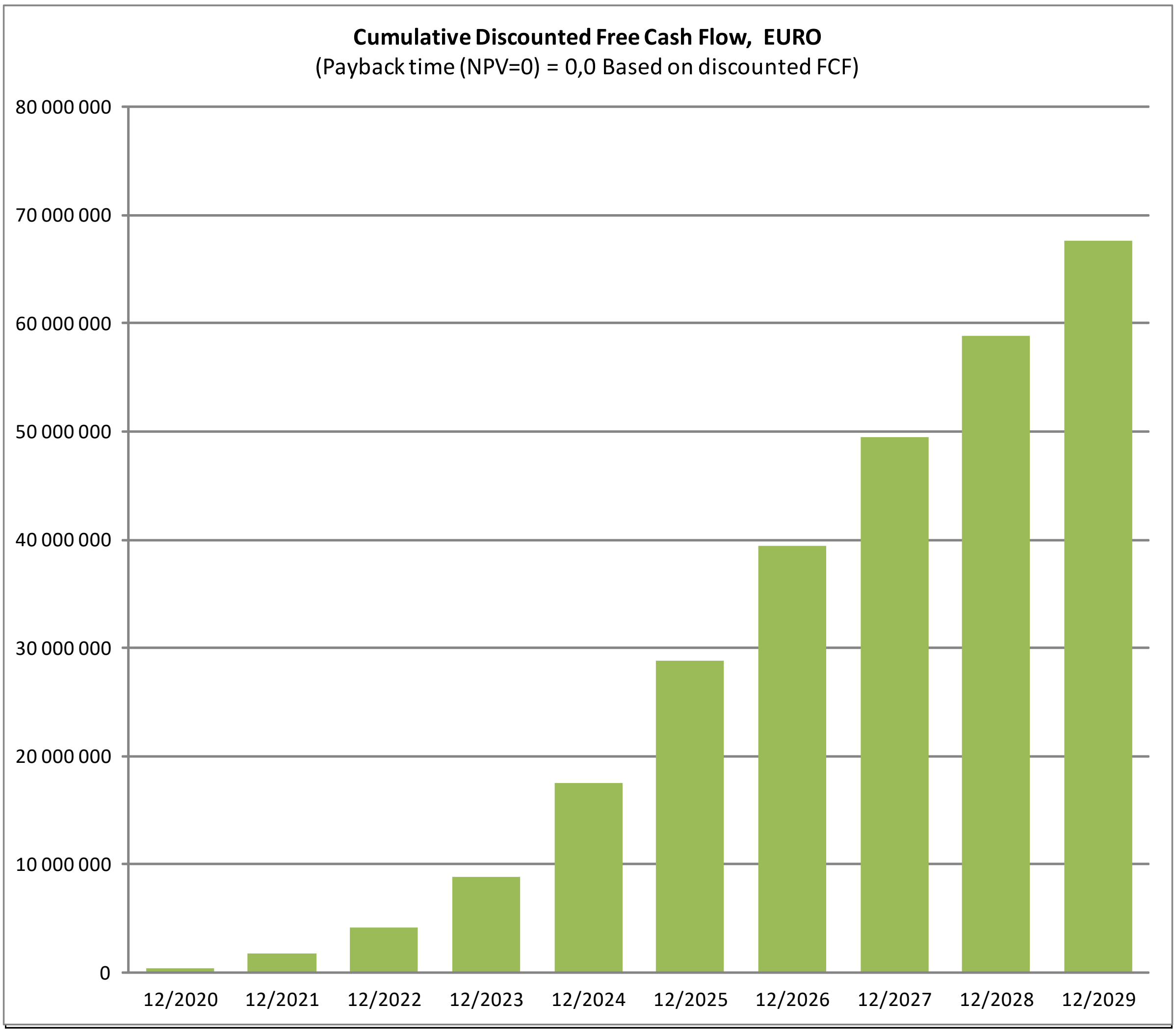
BASIC VALUES

Project description	Optimal option - production	
Calculation term, years	10 years	
Interval length, months	12	
Number of intervals	10	
	(MM/YYYY)	
Calculation term begins	01/2020	(in the beginning of period)
Calculation point	01/2020	(in the beginning of period)
Calculation term ends	12/2029	(in the end of the period)
Figures (1/1000/1000000)	1	
Currency	EURO	
Discount rate (per annum)	6,50	% (required rate of return)

	2020	2021	2022	2023	2024 ->
Income tax %	20	20	20	20	20

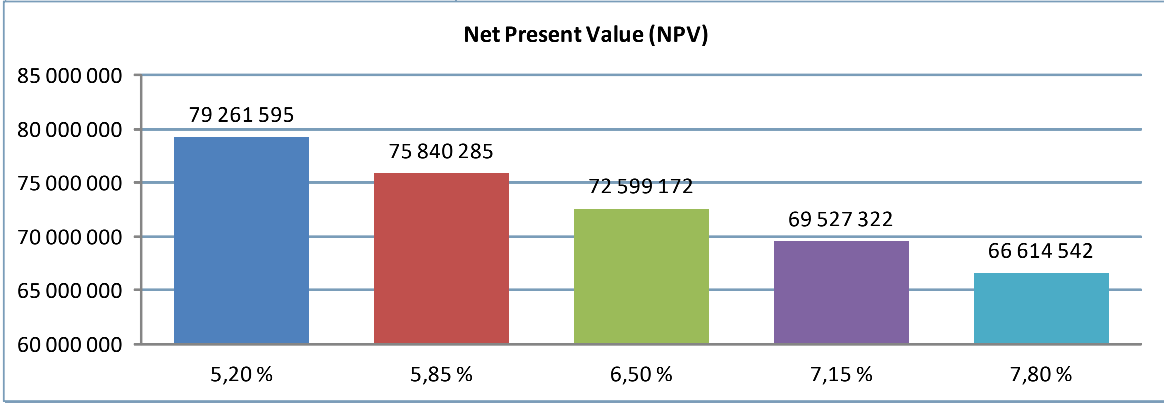
PROFITABILITY ANALYSIS

Project description	Optimal option - production			EURO
Nominal value of all investments		0	Discounted investments	0
Required rate of return		6,50 %		
Calculation term		10,0	years	1/2020 - 12/2029
Calculation point		1/2020	(In the beginning of period)	
Present value of business cash flows	Nominal	PV	Notes	
± PV of operative cash flow		67 627 062		
+ PV of residual value		4 972 110		
Present value of business cash flows		**72 599 172**		
- Present value of reinvestments	0	0		
Total Present Value (PV)		**72 599 172**		
Investment proposal	Nominal	PV		
- Proposed investments in assets	0	0		
+ Investment subventions	0	0		
Investment proposal	0	0		
Net Present Value (NPV)		**72 599 172**	>= 0	
NPV as a monthly annuity		817 496		
Internal Rate of Return (IRR)		-		
Modified Internal Rate of Return (MIRR)		-		
Profitability Index (PI)		-		
Payback time, years		0,0	Based on discounted FCF	
Return on net assets (RONA), %		251,0 %	Average 10 years	
Economic Value Added (EVA)		11 080 523	Average 10 years	
Discounted Value Added (DCVA)		72 345 820		
Internal Rate of Return based on DCVA (IRRd)				
Modified Internal Rate of Return based on DCVA (MIRRd)				
Payback time, years, based on DCVA		0,0		
Cumulative discounted value added 1/2020->1/2020		0		
Cumulative discounted value added 1/2020->12/2020		934 914		
Calculation point, Payback		1/2020		
Calculation is made by	ANDRZEJ PRYZOWICZ			2019-09-28
Calculation file	H:\AKTUALNE 2019\BIOPOLINEX AP\BIOPOLINEX_PROJEKTY\PROJEKT ARIES\REALIZACJA\ANALIZA SPRZEDAŻ SYSYTEMU_40MW_WARIANT_1_ENG.xlsm			


Cumulative Discounted Free Cash Flow, EURO
(Payback time (NPV=0) = 0,0 Based on discounted FCF)
80 000 000
70 000 000
60 000 000
50 000 000
40 000 000
30 000 000
20 000 000
10 000 000
0
12/2020
12/2021
12/2022
12/2023
12/2024
12/2025
12/2026
12/2027
12/2028
12/2029

Discount factor's impact on profitability

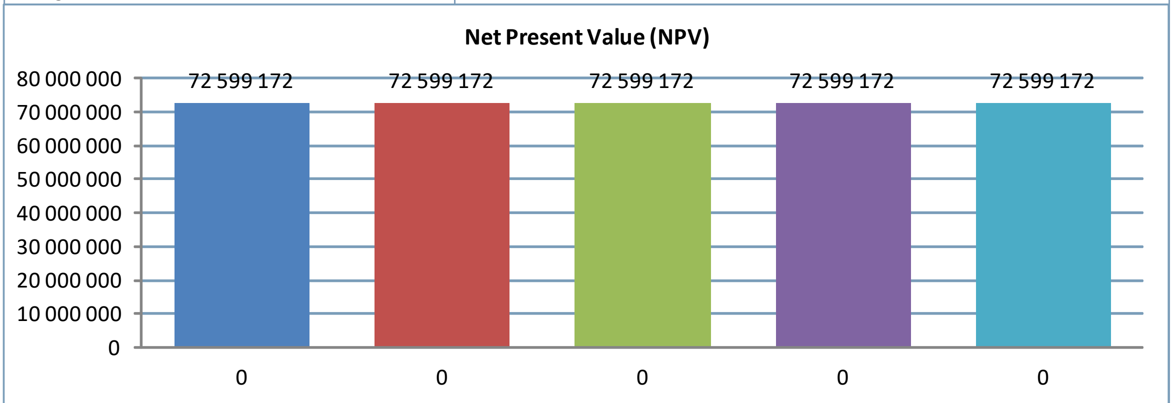
Discount factor	5,20 %	5,85 %	6,50 %	7,15 %	7,80 %
Change, %	-20,0 %	-10,0 %	0,0 %	+10,0 %	+20,0 %
Net Present Value (NPV)	79 261 595	75 840 285	72 599 172	69 527 322	66 614 542
Change, %	+9,2 %	+4,5 %	0,0 %	-4,2 %	-8,2 %



Key financials	5,20 %	5,85 %	6,50 %	7,15 %	7,80 %
EBITDA; Operating income before depreciation, EURO	1 292 000	1 292 000	1 292 000	1 292 000	1 292 000
EBITDA, %	18,5%	18,5%	18,5%	18,5%	18,5%
EBIT; Operating income, EURO	1 292 000	1 292 000	1 292 000	1 292 000	1 292 000
EBIT, %	18,5%	18,5%	18,5%	18,5%	18,5%
Return on net assets (RONA), %	221,49%	221,49%	221,49%	221,49%	221,49%
Economic Value Added (EVA), EURO	1 003 267	999 475	995 683	991 892	988 100

Total investment's impact on profitability

Total investment, EURO	0	0	0	0	0
Change, %	0,0 %	0,0 %	0,0 %	0,0 %	0,0 %
Net Present Value (NPV)	72 599 172	72 599 172	72 599 172	72 599 172	72 599 172
Change, %	0,0 %	0,0 %	0,0 %	0,0 %	0,0 %

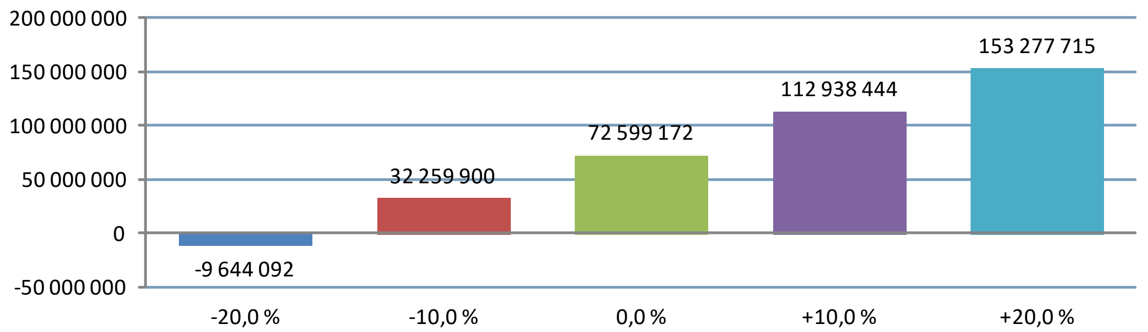


Key financials 12/2020	0	0	0	0	0
EBITDA; Operating income before depreciation, EURO	1 292 000	1 292 000	1 292 000	1 292 000	1 292 000
EBITDA, %	18,5%	18,5%	18,5%	18,5%	18,5%
EBIT; Operating income, EURO	1 292 000	1 292 000	1 292 000	1 292 000	1 292 000
EBIT, %	18,5%	18,5%	18,5%	18,5%	18,5%
Return on net assets (RONA), %	221,49%	221,49%	221,49%	221,49%	221,49%
Economic Value Added (EVA), EURO	995 683	995 683	995 683	995 683	995 683

Income's impact on profitability

Change in Income, %		-20,0 %	-10,0 %	0,0 %	+10,0 %	+20,0 %
Net Present Value (NPV)		-9 644 092	32 259 900	72 599 172	112 938 444	153 277 715
Change, %		-113,3 %	-55,6 %	0,0 %	+55,6 %	+111,1 %

Net Present Value (NPV)

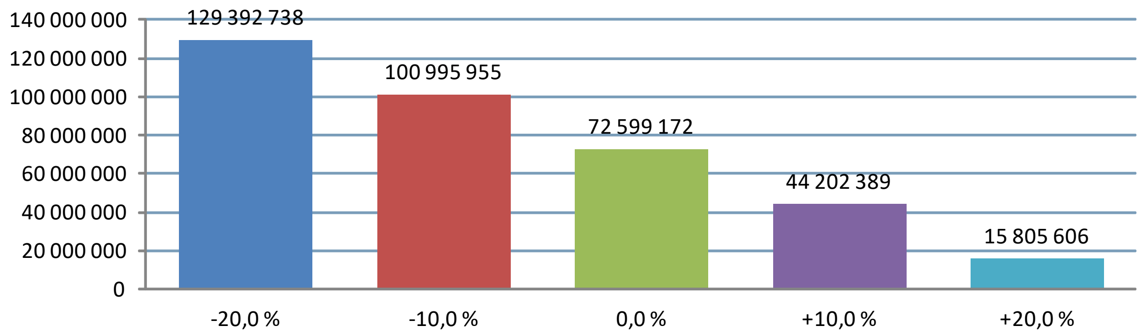


Key financials	12/2020	-20,00%	-10,00%	0,00%	+10,00%	+20,00%
EBITDA; Operating income before depreciation, EURO		-108 000	592 000	1 292 000	1 992 000	2 692 000
EBITDA, %		-1,9%	9,4%	18,5%	25,9%	32,0%
EBIT; Operating income, EURO		-108 000	592 000	1 292 000	1 992 000	2 692 000
EBIT, %		-1,9%	9,4%	18,5%	25,9%	32,0%
Return on net assets (RONA), %		-23,14%	112,76%	221,49%	310,44%	384,57%
Economic Value Added (EVA), EURO		-138 333	439 475	995 683	1 551 892	2 108 100

Variable cost's impact on profitability

Change in Variable costs, %		-20,0 %	-10,0 %	0,0 %	+10,0 %	+20,0 %
Net Present Value (NPV)		129 392 738	100 995 955	72 599 172	44 202 389	15 805 606
Change, %		+78,2 %	+39,1 %	0,0 %	-39,1 %	-78,2 %

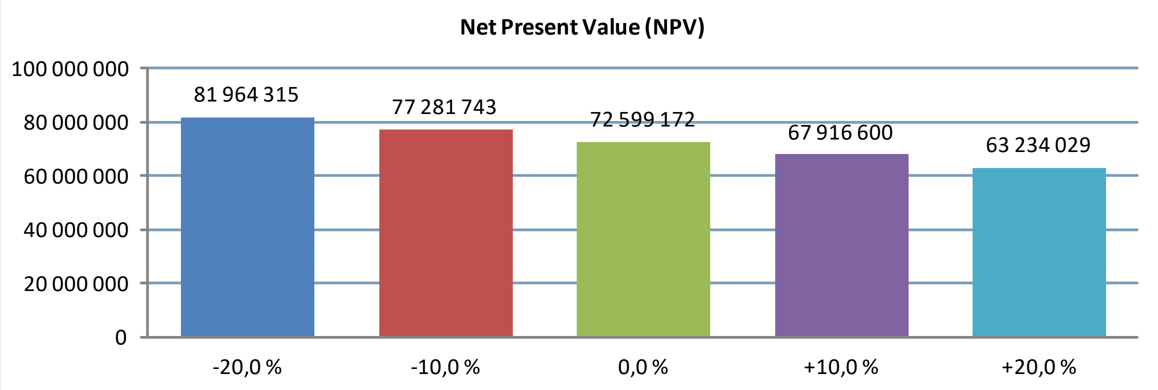
Net Present Value (NPV)



Key financials	12/2020	-20,0 %	-10,0 %	0,0 %	+10,0 %	+20,0 %
EBITDA; Operating income before depreciation, EURO		2 272 000	1 782 000	1 292 000	802 000	312 000
EBITDA, %		32,5%	25,5%	18,5%	11,5%	4,5%
EBIT; Operating income, EURO		2 272 000	1 782 000	1 292 000	802 000	312 000
EBIT, %		32,5%	25,5%	18,5%	11,5%	4,5%
Return on net assets (RONA), %		389,49%	305,49%	221,49%	137,49%	53,49%
Economic Value Added (EVA), EURO		1 779 683	1 387 683	995 683	603 683	211 683

Fixed cost's impact on profitability

Change in Fixed costs, %	-20,0 %	-10,0 %	0,0 %	+10,0 %	+20,0 %
Net Present Value (NPV)	81 964 315	77 281 743	72 599 172	67 916 600	63 234 029
Change, %	+12,9 %	+6,4 %	0,0 %	-6,4 %	-12,9 %



Key financials	12/2020	-20,0 %	-10,0 %	0,0 %	+10,0 %	+20,0 %
EBITDA; Operating income before depreciation, EURO		1 453 600	1 372 800	1 292 000	1 211 200	1 130 400
EBITDA, %		20,8%	19,6%	18,5%	17,3%	16,1%
EBIT; Operating income, EURO		1 453 600	1 372 800	1 292 000	1 211 200	1 130 400
EBIT, %		20,8%	19,6%	18,5%	17,3%	16,1%
Return on net assets (RONA), %		249,19%	235,34%	221,49%	207,63%	193,78%
Economic Value Added (EVA), EURO		1 124 963	1 060 323	995 683	931 043	866 403

9. Conclusions

For the purposes of the report the factor which was qualified as a comparative basis is a price of a low sulfur fuel in contrary to a price of regular fuel together with the purification cost.

As we may see in tabular calculations on page 36, NPV[15] for and optimal option is more than 12 €mm and for an optimistic scenario over 61 €mm and both IRR (53.3%) and MIRR (21.10%) definitely show the profitability of both optimistic and an optimal scenario.

From the other side, one may notice that if the parameters specified in the table on page 27 exceed, easy to identify, limit values, as e.g. investment value more than 7 €mm, vessel working hours less than 7 000 or fuel unit price less than 555 EUR/t, the investment becomes unprofitable.

[15] Net Present Value

The results of the analysis indicate the high market potential of the technology being developed.

A lot of parameters determine the level of fuel consumption by seagoing ships, as we may estimate even if we look at fuel value [EUR] or working hours of vessel.

Fuel consumption is a key parameter that determines the profitability of investments in exhaust gas purification.

The profitability analysis should be carried out for each ship separately. One must rely on data collected during the operation of the particular ship. Fuel consumption, at least, depends on:

- the size of the ship,
- engine power,
- speed,
- weariness,
- size of the cargo,
- navigation plan,
- cleanliness of low sides,
- trim,
- weather conditions

The sensitivity analysis showed the parameters related to the amount of fuel consumption are the most important and key factors determining profitability.

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Annex III

11. Attachements

Annex 1

detailed data optimal option, investment profitability analysis for the target customer.

INVESTMENTS (-) / REALIZATIONS (+)

Imputed depreciation		1/2020	12/2020	12/2021	12/2022	12/2023	12/2024	12/2025	12/2026	12/2027	12/2028	12/2029	Residual
Months per interval	Depr.-%		12	12	12	12	12	12	12	12	12	12	(12/2029)
1 **Investment value - hybrid system EB & scruber**			**-7 000 000**										**0**
Depreciation (straight line)	**10,00%**		-700 000	-700 000	-700 000	-700 000	-700 000	-700 000	-700 000	-700 000	-700 000	-700 000	
2													**0**
Depreciation (straight line)													
3													**0**
Depreciation (straight line)													
4													**0**
Depreciation (straight line)													
5													**0**
Depreciation (straight line)													
6													**0**
Depreciation (straight line)													
7													**0**
Depreciation (straight line)													
8													**0**
Depreciation (straight line)													
9													**0**
Depreciation (straight line)													
10													**0**
Depreciation (straight line)													
Investments		**0**	**-7 000 000**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	
Realizations		0	0	0	0	0	0	0	0	0	0	0	0
Depreciation		0	-700 000	-700 000	-700 000	-700 000	-700 000	-700 000	-700 000	-700 000	-700 000	-700 000	
Realization profit (+) / loss (-)		0	0	0	0	0	0	0	0	0	0	0	0
Book value		0	6 300 000	5 600 000	4 900 000	4 200 000	3 500 000	2 800 000	2 100 000	1 400 000	700 000	0	0

Annex III

INCOME STATEMENT

EURO		1/2020	12/2020	12/2021	12/2022	12/2023	12/2024	12/2025	12/2026	12/2027	12/2028	12/2029	Residual
Months per interval			12	12	12	12	12	12	12	12	12	12	(12/2029)
Income specified:													
Dodatkowe wydatki związane ze zmianą paliwa	EURO		5 600 000	5 600 000	5 600 000	5 600 000	5 600 000	5 600 000	5 600 000	5 600 000	5 600 000	5 600 000	
+ Amount of fuel consumed	t		28 000	28 000	28 000	28 000	28 000	28 000	28 000	28 000	28 000	28 000	
+ Working hours of the vessel	h		7 000	7 000	7 000	7 000	7 000	7 000	7 000	7 000	7 000	7 000	
* Unit fuel consumption	t/h		4,00	4,00	4,00	4,00	4,00	4,00	4,00	4,00	4,00	4,00	
Engine power	kW		40 000	40 000	40 000	40 000	40 000	40 000	40 000	40 000	40 000	40 000	
Power from the fuel unit	kg/kWh		0,100	0,100	0,100	0,100	0,100	0,100	0,100	0,100	0,100	0,100	
* Difference in fuel price	EURO/t		200	200	200	200	200	200	200	200	200	200	
+ Fuel price - LSMGO	EUR/t		555	555	555	555	555	555	555	555	555	555	
- Fuel price - IFO380	EUR/t		355	355	355	355	355	355	355	355	355	355	
Income		**0**	**5 600 000**	**5 600 000**	**5 600 000**	**5 600 000**	**5 600 000**	**5 600 000**	**5 600 000**	**5 600 000**	**5 600 000**	**5 600 000**	**0**
Other operating income													
Variable costs		0	-1 935 080	-1 935 080	-1 935 080	-1 935 080	-1 935 080	-1 935 080	-1 935 080	-1 935 080	-1 935 080	-1 935 080	0
Raw materials and consumables			-963 480	-963 480	-963 480	-963 480	-963 480	-963 480	-963 480	-963 480	-963 480	-963 480	
- Power costs of accelerator and scrubber	EURO		652 680	652 680	652 680	652 680	652 680	652 680	652 680	652 680	652 680	652 680	
+ Fuel unit price	EURO/t		555,00	555,00	555,00	555,00	555,00	555,00	555,00	555,00	555,00	555,00	
* Fuel consumption of the generator	t/year		1 176	1 176	1 176	1 176	1 176	1 176	1 176	1 176	1 176	1 176	
Unit fuel consumption of the generator	kg/kWh		0,14	0,14	0,14	0,14	0,14	0,14	0,14	0,14	0,14	0,14	
Accelerator and scrubber total power	kW		1 200	1 200	1 200	1 200	1 200	1 200	1 200	1 200	1 200	1 200	
Energy demand indicator	%		3,0%	3,0%	3,0%	3,0%	3,0%	3,0%	3,0%	3,0%	3,0%	3,0%	
- Costs of other consumables	EURO		310 800	310 800	310 800	310 800	310 800	310 800	310 800	310 800	310 800	310 800	
+ Calculation base - fuel value	EURO		15 540 000	15 540 000	15 540 000	15 540 000	15 540 000	15 540 000	15 540 000	15 540 000	15 540 000	15 540 000	
* Consumables costs indicator	%		2,0%	2,0%	2,0%	2,0%	2,0%	2,0%	2,0%	2,0%	2,0%	2,0%	
External charges	EURO		-350 000	-350 000	-350 000	-350 000	-350 000	-350 000	-350 000	-350 000	-350 000	-350 000	
- Service costs	EURO		350 000	350 000	350 000	350 000	350 000	350 000	350 000	350 000	350 000	350 000	
+ Investment value	EURO		7 000 000	7 000 000	7 000 000	7 000 000	7 000 000	7 000 000	7 000 000	7 000 000	7 000 000	7 000 000	
* Service costs indicator	%		5,0%	5,0%	5,0%	5,0%	5,0%	5,0%	5,0%	5,0%	5,0%	5,0%	
Staff costs													
Other variable costs	EURO		-621 600	-621 600	-621 600	-621 600	-621 600	-621 600	-621 600	-621 600	-621 600	-621 600	
- Other variable costs	EURO		15 540 000	15 540 000	15 540 000	15 540 000	15 540 000	15 540 000	15 540 000	15 540 000	15 540 000	15 540 000	
* Other variable costs indicator	%		4,0%	4,0%	4,0%	4,0%	4,0%	4,0%	4,0%	4,0%	4,0%	4,0%	
Gross margin		**0**	**3 664 920**	**3 664 920**	**3 664 920**	**3 664 920**	**3 664 920**	**3 664 920**	**3 664 920**	**3 664 920**	**3 664 920**	**3 664 920**	**0**
Gross margin, %			65,4%	65,4%	65,4%	65,4%	65,4%	65,4%	65,4%	65,4%	65,4%	65,4%	
Fixed costs		0	-566 000	-566 000	-566 000	-566 000	-566 000	-566 000	-566 000	-566 000	-566 000	-566 000	0
Staff costs			-216 000	-216 000	-216 000	-216 000	-216 000	-216 000	-216 000	-216 000	-216 000	-216 000	
- Number of employees	employees		3	3	3	3	3	3	3	3	3	3	
* Monthly rate	EUR/month		6 000	6 000	6 000	6 000	6 000	6 000	6 000	6 000	6 000	6 000	
* Number of months	months		12	12	12	12	12	12	12	12	12	12	
Rents													
Other fixed costs	EURO		-350 000	-350 000	-350 000	-350 000	-350 000	-350 000	-350 000	-350 000	-350 000	-350 000	

WORKING CAPITAL

EURO	1/2020	12/2020	12/2021	12/2022	12/2023	12/2024	12/2025	12/2026	12/2027	12/2028	12/2029	Residual
Months per interval		12	12	12	12	12	12	12	12	12	12	(12/2029)
Short-term assets												
Average term of payment, days		30	30	30	30	30	30	30	30	30	30	
Accounts receivable	0	466 667	466 667	466 667	466 667	466 667	466 667	466 667	466 667	466 667	466 667	0
Adjusted balance												
Increase (-) / decrease (+)	0	-466 667	0	0	0	0	0	0	0	0	0	466 667
Other receivables	0	0	0	0	0	0	0	0	0	0	0	
Change in other receivables, increase (-)/decrease (+)												0
Minimum cash	0	0	0	0	0	0	0	0	0	0	0	
Minimum cash, increase (-)/decrease (+)												0
Short-term assets, increase (-)/decrease (+)	0	-466 667	0	0	0	0	0	0	0	0	0	466 667
Inventories												
Turnover period, days		30	30	30	30	30	30	30	30	30	30	
Inventories	0	80 290	80 290	80 290	80 290	80 290	80 290	80 290	80 290	80 290	80 290	0
Adjusted balance												
Increase (-) / decrease (+)	0	-80 290	0	0	0	0	0	0	0	0	0	80 290
Inventories increase (-)/decrease (+)	0	-80 290	0	0	0	0	0	0	0	0	0	80 290
Current liabilities												
Average term of payment, days		30	30	30	30	30	30	30	30	30	30	
Accounts payable	0	109 457	109 457	109 457	109 457	109 457	109 457	109 457	109 457	109 457	109 457	0
Adjusted balance												
Increase (+) / decrease (-)	0	109 457	0	0	0	0	0	0	0	0	0	-109 457
Other current liabilities	0	0	0	0	0	0	0	0	0	0	0	
Change in other current liabilities, increase (+)/decr. (-)												0
Current liabilities increase (+)/decrease (-)	0	109 457	0	0	0	0	0	0	0	0	0	-109 457
Change in working capital	**0**	**-437 500**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**437 500**
Net working capital	0	437 500	437 500	437 500	437 500	437 500	437 500	437 500	437 500	437 500	437 500	0

CASH FLOW STATEMENT

EURO	1/2020	12/2020	12/2021	12/2022	12/2023	12/2024	12/2025	12/2026	12/2027	12/2028	12/2029	Residual
Months per interval		12	12	12	12	12	12	12	12	12	12	(12/2029)
Cash flow from operations												
Income	0	5 600 000	5 600 000	5 600 000	5 600 000	5 600 000	5 600 000	5 600 000	5 600 000	5 600 000	5 600 000	0
Variable costs	0	-1 935 080	-1 935 080	-1 935 080	-1 935 080	-1 935 080	-1 935 080	-1 935 080	-1 935 080	-1 935 080	-1 935 080	0
Fixed costs	0	-566 000	-566 000	-566 000	-566 000	-566 000	-566 000	-566 000	-566 000	-566 000	-566 000	0
Extraordinary income & expenses	0	0	0	0	0	0	0	0	0	0	0	0
Income tax (adjusted)	0	-479 784	-479 784	-479 784	-479 784	-479 784	-479 784	-479 784	-479 784	-479 784	-479 784	0
Change in working capital	0	-437 500	0	0	0	0	0	0	0	0	0	437 500
Cash flow from operations	**0**	**2 181 636**	**2 619 136**	**2 619 136**	**2 619 136**	**2 619 136**	**2 619 136**	**2 619 136**	**2 619 136**	**2 619 136**	**2 619 136**	**437 500**
Asset investments and realizations	0	-7 000 000	0	0	0	0	0	0	0	0	0	0
Free cash flow (FCF)	**0**	**-4 818 364**	**2 619 136**	**2 619 136**	**2 619 136**	**2 619 136**	**2 619 136**	**2 619 136**	**2 619 136**	**2 619 136**	**2 619 136**	**437 500**
Discounted free cash flow (DFCF)	0	-4 537 066	2 322 250	2 186 676	2 059 017	1 938 811	1 825 622	1 719 042	1 618 683	1 524 184	1 435 202	239 736
Cumulative discounted free cash flow	0	-4 537 066	-2 214 816	-28 139	2 030 878	3 969 689	5 795 311	7 514 353	9 133 036	10 657 220	12 092 422	12 332 158
Information												
Financial cash flow												
Financial income and expenses	0	-315 000	-210 000	-105 000	0	0	0	0	0	0	0	0
Correction of income tax for financial items	0	63 000	42 000	21 000	0	0	0	0	0	0	0	0
Long-term debt, increase (+) / decrease (-)	6 000 000	-1 500 000	-1 500 000	-1 500 000	-1 500 000	0	0	0	0	0	0	0
Changes in interest-bearing long-term debt	6 000 000	-1 500 000	-1 500 000	-1 500 000	-1 500 000	0	0	0	0	0	0	0
Long-term debt, increase (+) / decrease (-)	6 000 000	-1 500 000	-1 500 000	-1 500 000	-1 500 000							
Changes in long-term debt, Financing file												
Changes in interest-free long-term debt												
Changes in short-term borrowings												
Equity, increase (+) / decrease (-)	1 000 000	0	0	0	0	0	0	0	0	0	0	0
Changes in share capital	1 000 000											
Changes in share issue premium												
Changes in other restricted equity												
Changes in retained earnings												
Total cash flow	**7 000 000**	**-6 570 364**	**951 136**	**1 035 136**	**1 119 136**	**2 619 136**	**2 619 136**	**2 619 136**	**2 619 136**	**2 619 136**	**2 619 136**	**437 500**
Cumulative total cash flow	7 000 000	429 636	1 380 772	2 415 908	3 535 044	6 154 180	8 773 316	11 392 452	14 011 588	16 630 724	19 249 860	19 687 360

BALANCE SHEET

EURO	1/2020	12/2020	12/2021	12/2022	12/2023	12/2024	12/2025	12/2026	12/2027	12/2028	12/2029	Residual
Months per interval		12	12	12	12	12	12	12	12	12	12	(12/2029)
ASSETS												
Fixed assets and other non-current assets												
Intangible assets	0	0	0	0	0	0	0	0	0	0	0	0
Tangible assets	0	6 300 000	5 600 000	4 900 000	4 200 000	3 500 000	2 800 000	2 100 000	1 400 000	700 000	0	0
Investments	0	0	0	0	0	0	0	0	0	0	0	0
Total fixed assets and other non-current assets	0	6 300 000	5 600 000	4 900 000	4 200 000	3 500 000	2 800 000	2 100 000	1 400 000	700 000	0	0
Current Assets												
Inventories and work in progress	0	80 290	80 290	80 290	80 290	80 290	80 290	80 290	80 290	80 290	80 290	0
Accounts receivable	0	466 667	466 667	466 667	466 667	466 667	466 667	466 667	466 667	466 667	466 667	0
Other receivables	0	0	0	0	0	0	0	0	0	0	0	0
Bank and cash	7 000 000	429 636	1 380 772	2 415 908	3 535 044	6 154 180	8 773 316	11 392 452	14 011 588	16 630 724	19 249 860	19 687 360
Total current assets	7 000 000	976 593	1 927 729	2 962 865	4 082 001	6 701 137	9 320 273	11 939 409	14 558 545	17 177 681	19 796 817	19 687 360
ASSETS	**7 000 000**	**7 276 593**	**7 527 729**	**7 862 865**	**8 282 001**	**10 201 137**	**12 120 273**	**14 039 409**	**15 958 545**	**17 877 681**	**19 796 817**	**19 687 360**
SHAREHOLDERS' EQUITY AND LIABILITIES												
Shareholders' equity												
Share capital	1 000 000	1 000 000	1 000 000	1 000 000	1 000 000	1 000 000	1 000 000	1 000 000	1 000 000	1 000 000	1 000 000	1 000 000
Share issue premium	0	0	0	0	0	0	0	0	0	0	0	0
Other restricted equity	0	0	0	0	0	0	0	0	0	0	0	0
Retained earnings	0	0	1 667 136	3 418 272	5 253 408	7 172 544	9 091 680	11 010 816	12 929 952	14 849 088	16 768 224	16 768 224
Profit (loss) for the period	0	1 667 136	1 751 136	1 835 136	1 919 136	1 919 136	1 919 136	1 919 136	1 919 136	1 919 136	1 919 136	1 919 136
Total shareholders' equity	1 000 000	2 667 136	4 418 272	6 253 408	8 172 544	10 091 680	12 010 816	13 929 952	15 849 088	17 768 224	19 687 360	19 687 360
Appropriations	0	0	0	0	0	0	0	0	0	0	0	0
Provisions	0	0	0	0	0	0	0	0	0	0	0	0
Minority interest	0	0	0	0	0	0	0	0	0	0	0	0
Liabilities												
Long-term liabilities	4 500 000	3 000 000	1 500 000	0	0	0	0	0	0	0	0	0
Interest-bearing long-term debt	4 500 000	3 000 000	1 500 000	0	0	0	0	0	0	0	0	0
Interest-free long-term debt	0	0	0	0	0	0	0	0	0	0	0	0
Deferred tax liabilities	0	0	0	0	0	0	0	0	0	0	0	0
Short-term liabilities	1 500 000	1 609 457	1 609 457	1 609 457	109 457	109 457	109 457	109 457	109 457	109 457	109 457	0
Interest-bearing short-term liabilities	1 500 000	1 500 000	1 500 000	1 500 000	0	0	0	0	0	0	0	0
Short-term borrowings	0	0	0	0	0	0	0	0	0	0	0	0
Current portion of long-term loans	1 500 000	1 500 000	1 500 000	1 500 000	0	0	0	0	0	0	0	0
Interest-free short-term liabilities	0	109 457	109 457	109 457	109 457	109 457	109 457	109 457	109 457	109 457	109 457	0
Accounts payable	0	109 457	109 457	109 457	109 457	109 457	109 457	109 457	109 457	109 457	109 457	0
Other interest-free short-term debt	0	0	0	0	0	0	0	0	0	0	0	0
Accrued investment expenditure	0	0	0	0	0	0	0	0	0	0	0	0
Calculated tax debt	0	0	0	0	0	0	0	0	0	0	0	0
Total liabilities	6 000 000	4 609 457	3 109 457	1 609 457	109 457	109 457	109 457	109 457	109 457	109 457	109 457	0
SHAREHOLDERS' EQUITY AND LIABILITIES	**7 000 000**	**7 276 593**	**7 527 729**	**7 862 865**	**8 282 001**	**10 201 137**	**12 120 273**	**14 039 409**	**15 958 545**	**17 877 681**	**19 796 817**	**19 687 360**

Annex III

Optimal option - customer EURO

INCOME STATEMENT

	12/2020	12/2021	12/2022	12/2023	12/2024	12/2025	12/2026	12/2027	12/2028	12/2029
Continuing operations										
Sales	5 600 000	5 600 000	5 600 000	5 600 000	5 600 000	5 600 000	5 600 000	5 600 000	5 600 000	5 600 000
Other income	0	0	0	0	0	0	0	0	0	0
Materials and services	-963 480	-963 480	-963 480	-963 480	-963 480	-963 480	-963 480	-963 480	-963 480	-963 480
Employee benefit costs	-216 000	-216 000	-216 000	-216 000	-216 000	-216 000	-216 000	-216 000	-216 000	-216 000
Depreciation, amortisation and impairment charges	-700 000	-700 000	-700 000	-700 000	-700 000	-700 000	-700 000	-700 000	-700 000	-700 000
Other expenses	-1 321 600	-1 321 600	-1 321 600	-1 321 600	-1 321 600	-1 321 600	-1 321 600	-1 321 600	-1 321 600	-1 321 600
Operating profit	**2 398 920**	**2 398 920**	**2 398 920**	**2 398 920**	**2 398 920**	**2 398 920**	**2 398 920**	**2 398 920**	**2 398 920**	**2 398 920**
Share of profit of associates and joint ventures	0	0	0	0	0	0	0	0	0	0
Net financial items	-315 000	-210 000	-105 000	0	0	0	0	0	0	0
Profit before income tax	**2 083 920**	**2 188 920**	**2 293 920**	**2 398 920**	**2 398 920**	**2 398 920**	**2 398 920**	**2 398 920**	**2 398 920**	**2 398 920**
Income tax expense	-416 784	-437 784	-458 784	-479 784	-479 784	-479 784	-479 784	-479 784	-479 784	-479 784
Profit for the period from continuing operations	**1 667 136**	**1 751 136**	**1 835 136**	**1 919 136**	**1 919 136**	**1 919 136**	**1 919 136**	**1 919 136**	**1 919 136**	**1 919 136**
Discontinued operations										
Profit for the period from discontinued operations	0	0	0	0	0	0	0	0	0	0
Profit for the period	**1 667 136**	**1 751 136**	**1 835 136**	**1 919 136**	**1 919 136**	**1 919 136**	**1 919 136**	**1 919 136**	**1 919 136**	**1 919 136**
Attributable to:										
Equity holders of the company	1 667 136	1 751 136	1 835 136	1 919 136	1 919 136	1 919 136	1 919 136	1 919 136	1 919 136	1 919 136
Minority interest	0	0	0	0	0	0	0	0	0	0

Optimal option - customer EURO

BALANCE SHEET

	12/2020	12/2021	12/2022	12/2023	12/2024	12/2025	12/2026	12/2027	12/2028	12/2029
ASSETS										
Non-current assets										
Intangible assets	0	0	0	0	0	0	0	0	0	0
Property, plant and equipment	6 300 000	5 600 000	4 900 000	4 200 000	3 500 000	2 800 000	2 100 000	1 400 000	700 000	0
Investments in associates	0	0	0	0	0	0	0	0	0	0
Other long-term investments	0	0	0	0	0	0	0	0	0	0
Deferred tax assets	0	0	0	0	0	0	0	0	0	0
Long-term interest bearing receivables	0	0	0	0	0	0	0	0	0	0
Total non-current assets	**6 300 000**	**5 600 000**	**4 900 000**	**4 200 000**	**3 500 000**	**2 800 000**	**2 100 000**	**1 400 000**	**700 000**	**0**
Current assets										
Inventories	80 290	80 290	80 290	80 290	80 290	80 290	80 290	80 290	80 290	80 290
Trade and other receivables	466 667	466 667	466 667	466 667	466 667	466 667	466 667	466 667	466 667	466 667
Cash and cash equivalents	429 636	1 380 772	2 415 908	3 535 044	6 154 180	8 773 316	11 392 452	14 011 588	16 630 724	19 249 860
Total current assets	**976 593**	**1 927 729**	**2 962 865**	**4 082 001**	**6 701 137**	**9 320 273**	**11 939 409**	**14 558 545**	**17 177 681**	**19 796 817**
Total assets	**7 276 593**	**7 527 729**	**7 862 865**	**8 282 001**	**10 201 137**	**12 120 273**	**14 039 409**	**15 958 545**	**17 877 681**	**19 796 817**
EQUITY										
Capital and reserves attributable the Company's equity holders										
Share capital	1 000 000	1 000 000	1 000 000	1 000 000	1 000 000	1 000 000	1 000 000	1 000 000	1 000 000	1 000 000
Other equity	1 667 136	3 418 272	5 253 408	7 172 544	9 091 680	11 010 816	12 929 952	14 849 088	16 768 224	18 687 360
Total	**2 667 136**	**4 418 272**	**6 253 408**	**8 172 544**	**10 091 680**	**12 010 816**	**13 929 952**	**15 849 088**	**17 768 224**	**19 687 360**
Minority interest	0	0	0	0	0	0	0	0	0	0
Total equity	**2 667 136**	**4 418 272**	**6 253 408**	**8 172 544**	**10 091 680**	**12 010 816**	**13 929 952**	**15 849 088**	**17 768 224**	**19 687 360**
LIABILITIES										
Non-current liabilities										
Interest-bearing liabilities	3 000 000	1 500 000	0	0	0	0	0	0	0	0
Deferred tax liabilities	0	0	0	0	0	0	0	0	0	0
Provisions	0	0	0	0	0	0	0	0	0	0
Other liabilities	0	0	0	0	0	0	0	0	0	0
Total non-current liabilities	**3 000 000**	**1 500 000**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Current liabilities										
Interest-bearing liabilities	1 500 000	1 500 000	1 500 000	0	0	0	0	0	0	0
Current tax liability	0	0	0	0	0	0	0	0	0	0
Trade and other payables	109 457	109 457	109 457	109 457	109 457	109 457	109 457	109 457	109 457	109 457

Annex 2

detailed data optimal option, cost-effectiveness analysis for contractors and producers of installations

INVESTMENTS (-) / REALIZATIONS (+)

Imputed depreciation		1/2020	12/2020	12/2021	12/2022	12/2023	12/2024	12/2025	12/2026	12/2027	12/2028	12/2029	Residual
Months per interval	Depr.-%		12	12	12	12	12	12	12	12	12	12	(12/2029)
1 **Investment in system production**			**0**										**0**
Depreciation (straight line)	**10,00%**												
2													**0**
Depreciation (straight line)													
3													**0**
Depreciation (straight line)													
4													**0**
Depreciation (straight line)													
5													**0**
Depreciation (straight line)													
6													**0**
Depreciation (straight line)													
7													**0**
Depreciation (straight line)													
8													**0**
Depreciation (straight line)													
9													**0**
Depreciation (straight line)													
10													**0**
Depreciation (straight line)													
Investments		**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	
Realizations		0	0	0	0	0	0	0	0	0	0	0	0
Depreciation		0	0	0	0	0	0	0	0	0	0	0	
Realization profit (+) / loss (-)		0	0	0	0	0	0	0	0	0	0	0	0
Book value		0	0	0	0	0	0	0	0	0	0	0	0

Annex III

INCOME STATEMENT

EURO		1/2020	12/2020	12/2021	12/2022	12/2023	12/2024	12/2025	12/2026	12/2027	12/2028	12/2029	Residual
Months per interval			12	12	12	12	12	12	12	12	12	12	(12/2029)
Income specified:													
Przychody ze sprzedaży systemów oczyszczania spa	EURO		7 000 000	14 000 000	28 000 000	56 000 000	112 000 000	112 000 000	112 000 000	112 000 000	112 000 000	112 000 000	
+ Quantity of systems sold	pcs		1,00	2,00	4,00	8,00	16,00	16,00	16,00	16,00	16,00	16,00	
* Price	EURO/pcs		7 000 000	7 000 000	7 000 000	7 000 000	7 000 000	7 000 000	7 000 000	7 000 000	7 000 000	7 000 000	
Income		**0**	**7 000 000**	**14 000 000**	**28 000 000**	**56 000 000**	**112 000 000**	**112 000 000**	**112 000 000**	**112 000 000**	**112 000 000**	**112 000 000**	**0**
Other operating income													
Variable costs		0	-4 900 000	-9 800 000	-19 600 000	-39 200 000	-78 400 000	-78 400 000	-78 400 000	-78 400 000	-78 400 000	-78 400 000	0
Raw materials and consumables			-3 500 000	-7 000 000	-14 000 000	-28 000 000	-56 000 000	-56 000 000	-56 000 000	-56 000 000	-56 000 000	-56 000 000	
- The value of sales	EURO		7 000 000	14 000 000	28 000 000	56 000 000	112 000 000	112 000 000	112 000 000	112 000 000	112 000 000	112 000 000	
* Cost of materials indicator	%		50,0%	50,0%	50,0%	50,0%	50,0%	50,0%	50,0%	50,0%	50,0%	50,0%	
External charges													
Staff costs			-1 050 000	-2 100 000	-4 200 000	-8 400 000	-16 800 000	-16 800 000	-16 800 000	-16 800 000	-16 800 000	-16 800 000	
- The value of sales	EURO		7 000 000	14 000 000	28 000 000	56 000 000	112 000 000	112 000 000	112 000 000	112 000 000	112 000 000	112 000 000	
* Staff variable costs indicator	%		15,0%	15,0%	15,0%	15,0%	15,0%	15,0%	15,0%	15,0%	15,0%	15,0%	
Other variable costs			-350 000	-700 000	-1 400 000	-2 800 000	-5 600 000	-5 600 000	-5 600 000	-5 600 000	-5 600 000	-5 600 000	
- The value of sales	EURO		7 000 000	14 000 000	28 000 000	56 000 000	112 000 000	112 000 000	112 000 000	112 000 000	112 000 000	112 000 000	
* Other variable costs indicator	%		5,0%	5,0%	5,0%	5,0%	5,0%	5,0%	5,0%	5,0%	5,0%	5,0%	
Gross margin		**0**	**2 100 000**	**4 200 000**	**8 400 000**	**16 800 000**	**33 600 000**	**33 600 000**	**33 600 000**	**33 600 000**	**33 600 000**	**33 600 000**	**0**
Gross margin, %			30,0%	30,0%	30,0%	30,0%	30,0%	30,0%	30,0%	30,0%	30,0%	30,0%	
Fixed costs		0	-808 000	-1 616 000	-3 232 000	-6 464 000	-12 928 000	-12 928 000	-12 928 000	-12 928 000	-12 928 000	-12 928 000	0
Staff costs			-108 000	-216 000	-432 000	-864 000	-1 728 000	-1 728 000	-1 728 000	-1 728 000	-1 728 000	-1 728 000	
- Number of employees	1,5		2	3	6	12	24	24	24	24	24	24	
* Monthly rate	EUR/month		6 000	6 000	6 000	6 000	6 000	6 000	6 000	6 000	6 000	6 000	
* Number of months	months		12	12	12	12	12	12	12	12	12	12	
Rents													
Other fixed costs			-700 000	-1 400 000	-2 800 000	-5 600 000	-11 200 000	-11 200 000	-11 200 000	-11 200 000	-11 200 000	-11 200 000	
- The value of sales	EURO		7 000 000	14 000 000	28 000 000	56 000 000	112 000 000	112 000 000	112 000 000	112 000 000	112 000 000	112 000 000	
* Other fixed costs indicator	%		10,0%	10,0%	10,0%	10,0%	10,0%	10,0%	10,0%	10,0%	10,0%	10,0%	
Provisions, increase (-) / decrease (+)													
EBITDA; Operating income before depreciation		**0**	**1 292 000**	**2 584 000**	**5 168 000**	**10 336 000**	**20 672 000**	**20 672 000**	**20 672 000**	**20 672 000**	**20 672 000**	**20 672 000**	**0**
EBITDA, %			18,5%	18,5%	18,5%	18,5%	18,5%	18,5%	18,5%	18,5%	18,5%	18,5%	
Depreciation		0	0	0	0	0	0	0	0	0	0	0	0
EBIT; Operating income		**0**	**1 292 000**	**2 584 000**	**5 168 000**	**10 336 000**	**20 672 000**	**20 672 000**	**20 672 000**	**20 672 000**	**20 672 000**	**20 672 000**	**0**
EBIT, %			18,5%	18,5%	18,5%	18,5%	18,5%	18,5%	18,5%	18,5%	18,5%	18,5%	
Financing income and expenses		0	0	0	0	0	0	0	0	0	0	0	0
Financing income and expenses													
Financing income and expenses, Financing file													
EBT; Income after financing items		**0**	**1 292 000**	**2 584 000**	**5 168 000**	**10 336 000**	**20 672 000**	**20 672 000**	**20 672 000**	**20 672 000**	**20 672 000**	**20 672 000**	**0**

WORKING CAPITAL

EURO	1/2020	12/2020	12/2021	12/2022	12/2023	12/2024	12/2025	12/2026	12/2027	12/2028	12/2029	Residual
Months per interval		12	12	12	12	12	12	12	12	12	12	(12/2029)
Short-term assets												
Average term of payment, days		30	30	30	30	30	30	30	30	30	30	
Accounts receivable	0	583 333	1 166 667	2 333 333	4 666 667	9 333 333	9 333 333	9 333 333	9 333 333	9 333 333	9 333 333	0
Adjusted balance												
Increase (-) / decrease (+)	0	-583 333	-583 333	-1 166 667	-2 333 333	-4 666 667	0	0	0	0	0	9 333 333
Other receivables	0	0	0	0	0	0	0	0	0	0	0	
Change in other receivables, increase (-)/decrease (+)												0
Minimum cash	0	0	0	0	0	0	0	0	0	0	0	
Minimum cash, increase (-)/decrease (+)												0
Short-term assets, increase (-)/decrease (+)	0	-583 333	-583 333	-1 166 667	-2 333 333	-4 666 667	0	0	0	0	0	9 333 333
Inventories												
Turnover period, days		30	30	30	30	30	30	30	30	30	30	
Inventories	0	291 667	583 333	1 166 667	2 333 333	4 666 667	4 666 667	4 666 667	4 666 667	4 666 667	4 666 667	0
Adjusted balance												
Increase (-) / decrease (+)	0	-291 667	-291 667	-583 333	-1 166 667	-2 333 333	0	0	0	0	0	4 666 667
Inventories increase (-)/decrease (+)	0	-291 667	-291 667	-583 333	-1 166 667	-2 333 333	0	0	0	0	0	4 666 667
Current liabilities												
Average term of payment, days		30	30	30	30	30	30	30	30	30	30	
Accounts payable	0	291 667	583 333	1 166 667	2 333 333	4 666 667	4 666 667	4 666 667	4 666 667	4 666 667	4 666 667	0
Adjusted balance												
Increase (+) / decrease (-)	0	291 667	291 667	583 333	1 166 667	2 333 333	0	0	0	0	0	-4 666 667
Other current liabilities	0	0	0	0	0	0	0	0	0	0	0	
Change in other current liabilities, increase (+)/decr. (-)												0
Current liabilities increase (+)/decrease (-)	0	291 667	291 667	583 333	1 166 667	2 333 333	0	0	0	0	0	-4 666 667
Change in working capital	**0**	**-583 333**	**-583 333**	**-1 166 667**	**-2 333 333**	**-4 666 667**	**0**	**0**	**0**	**0**	**0**	**9 333 333**
Net working capital	0	583 333	1 166 667	2 333 333	4 666 667	9 333 333	9 333 333	9 333 333	9 333 333	9 333 333	9 333 333	0

CASH FLOW STATEMENT

EURO	1/2020	12/2020	12/2021	12/2022	12/2023	12/2024	12/2025	12/2026	12/2027	12/2028	12/2029	Residual
Months per interval		12	12	12	12	12	12	12	12	12	12	(12/2029)
Cash flow from operations												
Income	0	7 000 000	14 000 000	28 000 000	56 000 000	112 000 000	112 000 000	112 000 000	112 000 000	112 000 000	112 000 000	0
Variable costs	0	-4 900 000	-9 800 000	-19 600 000	-39 200 000	-78 400 000	-78 400 000	-78 400 000	-78 400 000	-78 400 000	-78 400 000	0
Fixed costs	0	-808 000	-1 616 000	-3 232 000	-6 464 000	-12 928 000	-12 928 000	-12 928 000	-12 928 000	-12 928 000	-12 928 000	0
Extraordinary income & expenses	0	0	0	0	0	0	0	0	0	0	0	0
Income tax	0	-258 400	-516 800	-1 033 600	-2 067 200	-4 134 400	-4 134 400	-4 134 400	-4 134 400	-4 134 400	-4 134 400	0
Change in working capital	0	-583 333	-583 333	-1 166 667	-2 333 333	-4 666 667	0	0	0	0	0	9 333 333
Cash flow from operations	**0**	**450 267**	**1 483 867**	**2 967 733**	**5 935 467**	**11 870 933**	**16 537 600**	**16 537 600**	**16 537 600**	**16 537 600**	**16 537 600**	**9 333 333**
Asset investments and realizations	0	0	0	0	0	0	0	0	0	0	0	0
Free cash flow (FCF)	**0**	**450 267**	**1 483 867**	**2 967 733**	**5 935 467**	**11 870 933**	**16 537 600**	**16 537 600**	**16 537 600**	**16 537 600**	**16 537 600**	**9 333 333**
Discounted free cash flow (DFCF)	0	422 786	1 308 265	2 456 835	4 613 775	8 664 367	11 333 782	10 642 048	9 992 534	9 382 661	8 810 010	4 972 110
Cumulative discounted free cash flow	0	422 786	1 731 050	4 187 886	8 801 661	17 466 028	28 799 809	39 441 858	49 434 391	58 817 052	67 627 062	72 599 172
Information												
Financial cash flow												
Financial income and expenses	0	0	0	0	0	0	0	0	0	0	0	0
Correction of income tax for financial items	0	0	0	0	0	0	0	0	0	0	0	0
Long-term debt, increase (+) / decrease (-)	0	0	0	0	0	0	0	0	0	0	0	0
Changes in short-term borrowings												
Equity, increase (+) / decrease (-)	0	0	0	0	0	0	0	0	0	0	0	0
Total cash flow	**0**	**450 267**	**1 483 867**	**2 967 733**	**5 935 467**	**11 870 933**	**16 537 600**	**16 537 600**	**16 537 600**	**16 537 600**	**16 537 600**	**9 333 333**
Cumulative total cash flow	0	450 267	1 934 133	4 901 867	10 837 333	22 708 267	39 245 867	55 783 467	72 321 067	88 858 667	105 396 267	114 729 600

BALANCE SHEET

EURO	1/2020	12/2020	12/2021	12/2022	12/2023	12/2024	12/2025	12/2026	12/2027	12/2028	12/2029	Residual
Months per interval		12	12	12	12	12	12	12	12	12	12	(12/2029)
ASSETS												
Fixed assets and other non-current assets												
Intangible assets	0	0	0	0	0	0	0	0	0	0	0	0
Tangible assets	0	0	0	0	0	0	0	0	0	0	0	0
Investments	0	0	0	0	0	0	0	0	0	0	0	0
Total fixed assets and other non-current assets	0	0	0	0	0	0	0	0	0	0	0	0
Current Assets												
Inventories and work in progress	0	291 667	583 333	1 166 667	2 333 333	4 666 667	4 666 667	4 666 667	4 666 667	4 666 667	4 666 667	0
Accounts receivable	0	583 333	1 166 667	2 333 333	4 666 667	9 333 333	9 333 333	9 333 333	9 333 333	9 333 333	9 333 333	0
Other receivables	0	0	0	0	0	0	0	0	0	0	0	0
Bank and cash	0	450 267	1 934 133	4 901 867	10 837 333	22 708 267	39 245 867	55 783 467	72 321 067	88 858 667	105 396 267	114 729 600
Total current assets	0	1 325 267	3 684 133	8 401 867	17 837 333	36 708 267	53 245 867	69 783 467	86 321 067	102 858 667	119 396 267	114 729 600
ASSETS	**0**	**1 325 267**	**3 684 133**	**8 401 867**	**17 837 333**	**36 708 267**	**53 245 867**	**69 783 467**	**86 321 067**	**102 858 667**	**119 396 267**	**114 729 600**
SHAREHOLDERS' EQUITY AND LIABILITIES												
Shareholders' equity												
Share capital	0	0	0	0	0	0	0	0	0	0	0	0
Share issue premium	0	0	0	0	0	0	0	0	0	0	0	0
Other restricted equity	0	0	0	0	0	0	0	0	0	0	0	0
Retained earnings	0	0	1 033 600	3 100 800	7 235 200	15 504 000	32 041 600	48 579 200	65 116 800	81 654 400	98 192 000	98 192 000
Profit (loss) for the period	0	1 033 600	2 067 200	4 134 400	8 268 800	16 537 600	16 537 600	16 537 600	16 537 600	16 537 600	16 537 600	16 537 600
Total shareholders' equity	0	1 033 600	3 100 800	7 235 200	15 504 000	32 041 600	48 579 200	65 116 800	81 654 400	98 192 000	114 729 600	114 729 600
Appropriations	0	0	0	0	0	0	0	0	0	0	0	0
Provisions	0	0	0	0	0	0	0	0	0	0	0	0
Minority interest	0	0	0	0	0	0	0	0	0	0	0	0
Liabilities												
Long-term liabilities	0	0	0	0	0	0	0	0	0	0	0	0
Short-term liabilities	0	291 667	583 333	1 166 667	2 333 333	4 666 667	4 666 667	4 666 667	4 666 667	4 666 667	4 666 667	0
Total liabilities	0	291 667	583 333	1 166 667	2 333 333	4 666 667	4 666 667	4 666 667	4 666 667	4 666 667	4 666 667	0
SHAREHOLDERS' EQUITY AND LIABILITIES	**0**	**1 325 267**	**3 684 133**	**8 401 867**	**17 837 333**	**36 708 267**	**53 245 867**	**69 783 467**	**86 321 067**	**102 858 667**	**119 396 267**	**114 729 600**

Annex III

Optimal option - production	**EURO**									
INCOME STATEMENT	**12/2020**	**12/2021**	**12/2022**	**12/2023**	**12/2024**	**12/2025**	**12/2026**	**12/2027**	**12/2028**	**12/2029**
Continuing operations										
Sales	7 000 000	14 000 000	28 000 000	56 000 000	112 000 000	112 000 000	112 000 000	112 000 000	112 000 000	112 000 000
Other income	0	0	0	0	0	0	0	0	0	0
Materials and services	-3 500 000	-7 000 000	-14 000 000	-28 000 000	-56 000 000	-56 000 000	-56 000 000	-56 000 000	-56 000 000	-56 000 000
Employee benefit costs	-1 158 000	-2 316 000	-4 632 000	-9 264 000	-18 528 000	-18 528 000	-18 528 000	-18 528 000	-18 528 000	-18 528 000
Depreciation, amortisation and impairment charges	0	0	0	0	0	0	0	0	0	0
Other expenses	-1 050 000	-2 100 000	-4 200 000	-8 400 000	-16 800 000	-16 800 000	-16 800 000	-16 800 000	-16 800 000	-16 800 000
Operating profit	**1 292 000**	**2 584 000**	**5 168 000**	**10 336 000**	**20 672 000**	**20 672 000**	**20 672 000**	**20 672 000**	**20 672 000**	**20 672 000**
Share of profit of associates and joint ventures	0	0	0	0	0	0	0	0	0	0
Net financial items	0	0	0	0	0	0	0	0	0	0
Profit before income tax	**1 292 000**	**2 584 000**	**5 168 000**	**10 336 000**	**20 672 000**	**20 672 000**	**20 672 000**	**20 672 000**	**20 672 000**	**20 672 000**
Income tax expense	-258 400	-516 800	-1 033 600	-2 067 200	-4 134 400	-4 134 400	-4 134 400	-4 134 400	-4 134 400	-4 134 400
Profit for the period from continuing operations	**1 033 600**	**2 067 200**	**4 134 400**	**8 268 800**	**16 537 600**	**16 537 600**	**16 537 600**	**16 537 600**	**16 537 600**	**16 537 600**
Discontinued operations										
Profit for the period from discontinued operations	0	0	0	0	0	0	0	0	0	0
Profit for the period	**1 033 600**	**2 067 200**	**4 134 400**	**8 268 800**	**16 537 600**	**16 537 600**	**16 537 600**	**16 537 600**	**16 537 600**	**16 537 600**
Attributable to:										
Equity holders of the company	1 033 600	2 067 200	4 134 400	8 268 800	16 537 600	16 537 600	16 537 600	16 537 600	16 537 600	16 537 600
Minority interest	0	0	0	0	0	0	0	0	0	0

Optimal option - production	**EURO**									
BALANCE SHEET	**12/2020**	**12/2021**	**12/2022**	**12/2023**	**12/2024**	**12/2025**	**12/2026**	**12/2027**	**12/2028**	**12/2029**
ASSETS										
Non-current assets										
Intangible assets	0	0	0	0	0	0	0	0	0	0
Property, plant and equipment	0	0	0	0	0	0	0	0	0	0
Investments in associates	0	0	0	0	0	0	0	0	0	0
Other long-term investments	0	0	0	0	0	0	0	0	0	0
Deferred tax assets	0	0	0	0	0	0	0	0	0	0
Long-term interest bearing receivables	0	0	0	0	0	0	0	0	0	0
Total non-current assets	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Current assets										
Inventories	291 667	583 333	1 166 667	2 333 333	4 666 667	4 666 667	4 666 667	4 666 667	4 666 667	4 666 667
Trade and other receivables	583 333	1 166 667	2 333 333	4 666 667	9 333 333	9 333 333	9 333 333	9 333 333	9 333 333	9 333 333
Cash and cash equivalents	450 267	1 934 133	4 901 867	10 837 333	22 708 267	39 245 867	55 783 467	72 321 067	88 858 667	105 396 267
Total current assets	**1 325 267**	**3 684 133**	**8 401 867**	**17 837 333**	**36 708 267**	**53 245 867**	**69 783 467**	**86 321 067**	**102 858 667**	**119 396 267**
Total assets	**1 325 267**	**3 684 133**	**8 401 867**	**17 837 333**	**36 708 267**	**53 245 867**	**69 783 467**	**86 321 067**	**102 858 667**	**119 396 267**
EQUITY										
Capital and reserves attributable the Company's equity holders										
Share capital	0	0	0	0	0	0	0	0	0	0
Other equity	1 033 600	3 100 800	7 235 200	15 504 000	32 041 600	48 579 200	65 116 800	81 654 400	98 192 000	114 729 600
Total	**1 033 600**	**3 100 800**	**7 235 200**	**15 504 000**	**32 041 600**	**48 579 200**	**65 116 800**	**81 654 400**	**98 192 000**	**114 729 600**
Minority interest	0	0	0	0	0	0	0	0	0	0
Total equity	**1 033 600**	**3 100 800**	**7 235 200**	**15 504 000**	**32 041 600**	**48 579 200**	**65 116 800**	**81 654 400**	**98 192 000**	**114 729 600**
LIABILITIES										
Non-current liabilities										
Interest-bearing liabilities	0	0	0	0	0	0	0	0	0	0
Deferred tax liabilities	0	0	0	0	0	0	0	0	0	0
Provisions	0	0	0	0	0	0	0	0	0	0
Other liabilities	0	0	0	0	0	0	0	0	0	0
Total non-current liabilities	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Current liabilities										
Interest-bearing liabilities	0	0	0	0	0	0	0	0	0	0
Current tax liability	0	0	0	0	0	0	0	0	0	0
Trade and other payables	291 667	583 333	1 166 667	2 333 333	4 666 667	4 666 667	4 666 667	4 666 667	4 666 667	4 666 667

DEVELOPMENT OF A HYBRID ELECTRON ACCELERATOR SYSTEM FOR THE TREATMENT OF MARINE DIESEL EXHAUST GASES

T. Torims*, G. Pikurs, K. Kravalis, A. Ruse, Riga Technical University, Latvia
A.G. Chmielewski, A. Pawelec, Z. Zimek, Institute of Nuclear Chemistry and Technology, Poland
G. Mattausch, Fraunhofer Institute for Organic Electronics, Electron Beam and Plasma Technology FEP, Germany
M. Vretenar, CERN, Switzerland

Abstract

The paper outlines the overall results of the ARIES Proof-of-Concept (PoC) project,[1] which seeks to tackle the shipping industry's most pressing problem, its large-scale emissions of nitrogen oxides (NO_x), sulphur oxides (SO_x) and particulate matter (PM), by developing a hybrid exhaust gas-cleaning technology that combines an EB accelerator with improved wet-scrubbing technology [1]. It is unique – in a single technological system – and addresses all three types of emissions simultaneously. It promises to be cheaper and more efficient than existing solutions. There are two main stages involved: 1) SO_2 and NO_x oxidation during the irradiation of wet gases by the EB from the accelerator and 2) the absorption of pollution products into an aqueous solution. For the very first time, test trials in a real maritime environment were conducted and attracted the interest of the maritime industry, policy makers and the accelerator community. The PoC has clearly confirmed the potential of this technology and forms a solid basis for the full-scale application of the hybrid system on sea-going ships. The results of this project are of the highest relevance to the accelerator community, as well as the maritime industry and policy makers.

MOTIVATION AND CONTEXT

Heavy fuel oil (HFO) is the main energy source used by the maritime industry. Almost all medium and low-speed marine diesel engines run on HFO with a high sulphur content, leading to the formation of three main pollutants: NO_x, SO_x and PM. These emissions have been gradually restricted worldwide. When entering Emission Control Areas (ECA) or ports, ships switch to 0.1% sulphur content fuel, marine gasoil (MGO). Since 2020, maritime transport has had to comply with the worldwide 0.5% emission sulphur cap, under MARPOL Annex VI Regulation 14.

In the North America ECA, not only SO_x, but also NO_x and PM have been regulated and the North/Baltic Sea Sulphur ECA will be in place from 2021. A similar policy initiative is currently undertaken in the Mediterranean Sea [2]. These are so-called Tier III requirements, limiting NO_x emissions to between 3.4 and 2 g/kWh. It is expected that further requirements for significant PM reductions will be imposed [3]. The maritime community faces a serious challenge to fulfil these limitations [4].

Existing technologies and prior attempts

Cutting SO_x. To comply with sulphur emission limitations [5], the shipping industry currently has two workable options [6]: a) to opt for universal usage of expensive MGO, or b) to install exhaust gas cleaning systems (scrubbers), which reduce SO_x and PM emissions from ship engines, generators and boilers, allowing ships to continue using HFO.

However, there may be pertinent operational issues involved in running marine engines designed for HFO continuously on MGO and the price difference between the two could considerably increase shipping costs. Today scrubbers are the preferred solution to comply with SOx limitations, hence there is a growing incentive for ship owners to invest in scrubbers. However, implementation costs are very high—1M to 5M EUR for the equipment [7] alone. Therefore, in the absence of a more cost-effective technological solution, it will be very challenging in the near future to equip the global fleet of about 60,000 vessels.

Dealing with NOx. NO_x production is not directly related to the type of fuel, but to the combustion process itself. Switching to MGO therefore doesn't solve this issue. In order to achieve NO_x emission compliance, some form of additional technology has to be installed on-board. Usually this is a costly and complicated, selective catalytic reduction (SCR) system. Naturally, marine scrubbing and denitration systems are expected to be compatible, although this is not the case. As such, ships are being equipped with two separate purifying systems: one for SO_x and another for NO_x.

PM trapping. The most common methods for removing PM from exhaust fumes are the Continuously Regenerating Trap, Diesel Particulate Filter and Diesel Oxidation Catalyst. However, they can only be used for emissions from low-sulphur fuels. Also the nanoparticles, the most harmful form of PM (e.g. PM_{10} and $PM_{2.5}$) are not sufficiently prevented from entering the ambient air.

Prior attempts. The ship-emission challenge is not new *per se*; there have been various efforts to find feasible alternatives, such as the Humid Air Motor, Exhaust Gas Recirculation, Plasma-Catalysis, Nano-Membrane Filters, etc. Several of these projects [8, 9,10,11,12] were EU financed and presented to the stakeholders. Yet to this day, they cannot be cost-effectively installed on ships. These alternative methods typically target SO_X, and neglect NO_x, PM, volatile organic compounds (VOC) and hazardous polycyclic aromatic hydrocarbons (PAH). To date, only a

* toms.torims@rtu.lv

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few studies have been conducted on the simultaneous removal of NO_x and SO_2 in a single process [13,14,15,16]. They mostly rely on the use of electrolysis and electromagnetic techniques, but have not resulted in uptake by the maritime industry.

Novel hybrid accelerator technology

The proposed technology is fundamentally different and could help to address the global challenge of air pollution and emission cuts. It is based on pollutant removal by combining two correlated technological stages (see Fig.1.), electron beam irradiation (EB) of flue gas with subsequent wet-chemical scrubbing [17,18]:

EB irradiation: electrons are accelerated by a high voltage in a vacuum, before being injected through thin foil windows into the exhaust gases in the atmospheric pressure processing chamber. The energetic electrons collide with exhaust gas molecules and produce reactive free radicals, atoms, ions and secondary electrons that decompose the pollutant molecules in the irradiated exhaust gases. These excited species and radicals react with NO and SO_2 to form their higher oxidation compounds: NO mainly forms NO_2, then by increasing the applied dose becomes NO_3 and SO_2 forms SO_3. Due to the high water-vapour concentration in the exhaust gas, HNO_3 and H_2SO_4 are formed and are easily soluble in the scrubbing liquid. Additionally, PM and organic pollutants like VOC and PAH are effectively eliminated by EB-formed plasma [19,20].

Wet scrubber: subsequently the pollution products from the exhaust gases are absorbed into an aqueous solution - in a closed-loop wet scrubber. The seawater is used as the scrubbing solution, with the limited addition of liquid oxidant (e.g. $NaClO_2$) to scrub soluble products from the oxidation reactions [21]. Wash water after cleaning is recirculated. If the SO_2 inlet concentration is high, the removal efficiency of NO increases noticeably, especially at a higher irradiation dose range. The effect of the presence of SO_2 in enhancing NO_x removal efficiency can be explained by the chain of reactions - HO_2 radicals, which are produced during reactions with SO_2, react with NO and oxidize them into NO_2. This in turn is later converted to HNO_3. Therefore, when the NO inlet concentration is high, as in the case of HFO, this synergistic effect is more advantageous at high SO_2 concentrations.

From science to society - transfer of technology

Relevance to the Accelerator Community initiatives. This endeavour was possible due to a genuine commitment among the Accelerator Community to develop societal accelerator applications. EB environmental applications have been addressed in the "Applications of Particle Accelerators in Europe" [22]. Equally the role of particle accelerators to meet the needs of society at large is emphasised in "Accelerators for America's" [23]. This idea has been elaborated further in the ARIES project under "Industrial and Societal Applications" [24].

Matching Maritime Policy and Industry needs. The maritime industry is looking for suitable, economically effective and fast solutions for *green shipping*. Despite various policy actions [25,26,27,28], so far they have met with limited success. Therefore, considering that *inter alia* the European shipping industry welcomes the European Green Deal [29], this hybrid technology is offering a tangible solution for the maritime industry and its stakeholders' needs.

Economic feasibility. In order to make this hybrid technology attractive to the maritime industry and prove its feasibility to policy makers, unbiased cost effectiveness analysis is needed. It is not enough to show operationally that this technology works; its clear business case must be established. This is a decisive factor, along with safety considerations, for the acceptance and further uptake of the technology. This innovative technology could be proliferated only if it is less costly than the combined cost of existing marine SO_x and NO_x abatement solutions and fulfils all the relevant maritime safety requirements.

PROOF OF CONCEPT

The magnitude of this societal challenge goes far beyond the capacity of any individual research institution or company and requires a wide collaborative effort. Therefore, a multidisciplinary *Collaboration* was summoned: partners with world-class expertise in accelerator and maritime technologies, shipping and economic analysis have teamed up to offer an alternative for *green shipping*.

The **Virtue** of this project is its connection of two distinct communities: maritime and accelerator specialists. This is not merely a scientific or technological undertaking, bringing particle accelerators onboard ships. It is also an opportunity for the accelerator community to understand the compliance requirements of the shipping industry and marine engineering, as well as for the maritime community to build trust with the established research institutions and scientific community.

Commitment. Through its multidisciplinary and multisectoral composition, the actual collaboration demonstrates the potential of the hybrid system's application onboard ships. Importantly, the partners have greatly contributed their own resources—this clearly demonstrates aspiration—especially from the maritime community. The total budget of the PoC project was 0.5M EUR, of which about 90% were direct contributions from partners and only 10% was EC contribution. This resulted in a great collaborative spirit within this partnership, building multilateral trust and commitment to continue development of the hybrid technology until its full implementation onboard ships.

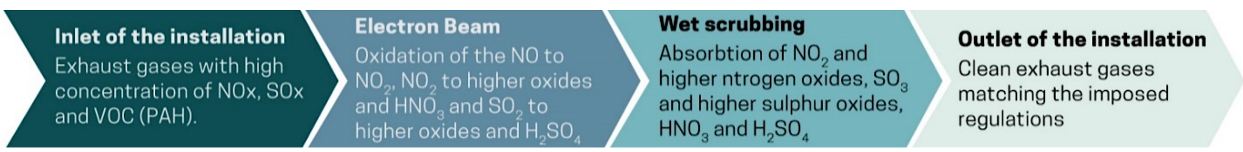

Figure 1: Principle of the hybrid electron accelerator technology for the treatment of marine diesel exhaust gases.

Engaging stakeholders. To ensure that contact with reality was maintained, from the outset this project was exposed to the rigorous scrutiny of stakeholders. Naturally, development of the hybrid off-gas cleaning system has pushed back existing technological and acceptance boundaries. Therefore, the partners are engaging with the EC, IMO, IACS, EGCSA, TIARA consortium and others. The Italian Coast Guard and ABS are also directly participating in an advisory capacity.

Objectives. The collaboration is aiming to expand particle accelerator technologies into the maritime domain by developing the said technology. This requires demonstration and validation, to provide the maritime industry with a much-needed innovative, cost-effective solution that would substantially improve the environmental performance of fleets, by significantly reducing ship emissions. In order to achieve this *green shipping* goal, the PoC project was tasked with the following pivotal objectives:

1. To conceptually prove the electron-beam accelerator application for the effective treatment of marine diesel exhaust gases.
2. To prove its technical feasibility within the real ship environment—advance the technology to TRL3.
3. To demonstrate that the technology in question is capable of removing sufficient levels of SO_x and NO_x.
4. To provide a sound financial evaluation of the cost-effectiveness of this technology.
5. To engage with and inform all relevant stakeholders during the project.

CONCEPT AND EXPERIMENTAL SET-UP

Methodology. The demonstration was performed using a mobile platform of the linear type of accelerator, directly connected to the ship exhaust duct. Crucial flue gas parameters were measured: flue gas velocity, flue gas temperature and flue gas composition (see Fig.2).

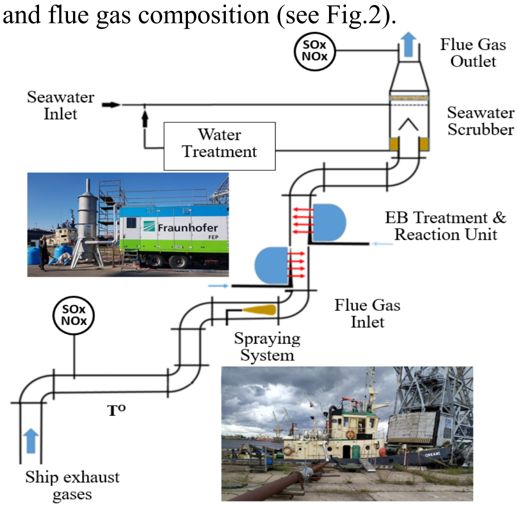

Figure 2: Hybrid Electron Accelerator System.

Of all the generally accepted methods for considering the mass exchange process, in this case the most appropriate is to quantify the mass exchange process, including absorption efficiency (see Eq.1). This value offers a simple and transparent way to assess the impact of the main process parameters on the effectiveness of gas treatment. It has been assumed that the absorption efficiency is a function of the following variables:

$$\eta = f(Ue, L/G, H, Co, Cr). \qquad (1)$$

where η - absorption efficiency [%], *Ue* - gas velocity calculated on the empty column cross-section [m/s], *L/G* - spraying density of the absorption solution, litres of solution per cubic meter of gas [L/m^3], *H* - column packing height [m], *Co* - initial concentration of NO_x (calculated as NO_2) in the gas, [mg/m^3] or [vol%], and *Cr* - concentration of the absorption solution, [kg/m^3] or [mass%].

Pilot installation. A fully operational tugboat “Orkāns” berthed at the pier of Riga Ship Yard was used as the source of flue gas. This ship is equipped with double two-stroke 450 kW Diesel engines. The outlet of the exhaust gas duct was flexibly connected to the accelerator complex by a 320 mm diameter pipeline of almost 20 m in length.

A mobile accelerator unit WESENITZ-II was provided by Fraunhofer FEP and used as an EB irradiation device. The facility is usually operated for seed dressing, but was modified for flue gas treatment. The irradiation chamber was of rectangular cross section (120 x 1560 mm²) and 1180 mm in height. The exhaust gas flowed vertically from bottom to top and was irradiated from both sides by means of two 125 kV EB accelerators. The maximal current for one accelerator was 100 mA. A single 10 µm Ti foil facilitated the electron exit into the irradiation chamber. It was cooled and protected against condensates and PM by an intense tangential air flow curtain. In order to protect the accelerator unit against potentially excessive gas temperatures, a spray cooler was installed in the connecting pipeline between the ship and the accelerator. In the course of experiments however, it was proven that the air curtain alone sufficiently protects the thin electron window foil.

A counter-current gas-liquid flow packed closed-loop scrubber was selected as the absorber for the purposes of this project. The device of 1.2 m diameter and 5.5 m height was filled with *Bialecki* rings. The filling height was 2.6 m. The circulating water was stored in two tanks filled with 3 m^3 of seawater. The Baltic Sea water from the tanks was filtered and pumped to a system of nozzles located at the top of the scrubber and sprayed into the top of the scrubber, then flowed to the bottom of the device and back to the tank by gravity. The gas from the irradiation unit was directed to the lower part of the scrubber and released into the atmosphere by a stack located at the top of the device. In order to maintain the water’s ability to absorb acidic gases, its pH was kept above 7.5 by the addition of sodium hydroxide. To enhance the oxidation potential and improve NO_x removal efficiency, an oxidant ($NaClO_2$) was also added to the water. The tested oxidant concentration was in the range of 0 – 3.3 mg/L (see Fig.3).

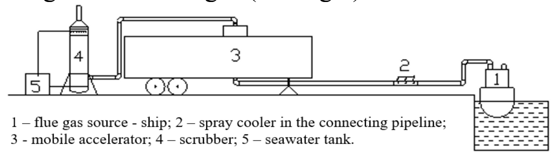

Figure 3. General scheme of pilot installation.

Measurements. All of the flue gas generated by the ship's engine was treated in the system. The experiments were conducted for three engine loads (0% - idling run, 50% and 100%). The flue gas sampling points were located upstream of the accelerator, at the exit of the scrubber and at the gas outlet stack. In this way, the gas composition was measured at the inlet of the installation, after irradiation and after treatment at the outlet of the system. Moreover, five temperature measurement points were installed: downstream from the engine, upstream of the spray cooler, at the irradiation unit gas inlet, the scrubber inlet and the scrubber gas outlet, along with a gas velocity measurement point, before irradiation.

Economic feasibility. A comprehensive economic and financial analysis was carried out by an independent assessor Biopolinex - from the point of view of the end user and the manufacturer of the accelerator system. The investment profitability was assessed on the basis of discounted cash flows, Net Present Value (NPV), Internal Rate of Return (IRR) and repayment period. The breakeven point was calculated. The result was validated by a sensitivity analysis of the volatility of the key financial parameters.

RESULTS AND CONCLUSIONS

Engineering. The most important achievement of the PoC was the technical integration of the diesel engine, with the upstream accelerator process chamber, where Ti foil was protected by an air curtain and a wet scrubber downstream. The flow of flue gases was induced by diesel engine over pressure, which induced proper gas flow against pressure drop for all the process installation components. The accelerator complex and protection windows with titanium foils were not damaged by the high temperature off-gas flow. Earlier lab experiments were successfully validated, and the analytical methods were tested. This successful operation of a ship-port based installation verified the assumptions that are fundamental to continuing the project for the full on-board system development.

Collaboration of Riga Technical University, Institute of Nuclear Chemistry and Technology, CERN, Fraunhofer Institute for Organic Electronics, Electron Beam and Plasma Technology FEP, Remontowa Marine Design, Riga Ship Yard and Biopolinex by its commitment and dedicated efforts of the core team enabled us to achieve all the objectives set for the PoC. Notably, it demonstrated that for the very first time, the two underlying technologies for the envisaged system (accelerators and scrubbers) can be combined in a real maritime environment – reaching TRL 3 – instrumental for the green shipping policy.

Conclusions

The **economic analysis** confirmed the profitability of the hybrid technology vis-à-vis the HFO option with the conventional scrubber off-gases abatement costs. This is true for both *optimistic* and *optimal* financial risk associated scenarios, indicating the high market potential of the maritime application of the hybrid technology.

Abatement of NO_x and SO_x. Although, the environmental and operational restrictions of the port only allowed for the usage of desulfurized (eventually SO_x free) marine fuel, even with a non-homogeneous and moderate irradiation dose, a significant reduction of up to 45.8% of NO_x was recorded (see selected results in Table 1 and overall in Fig.4 and Fig.5). This was matched by the measurement profiles of the other exhaust gases family parameters and matched with the analytical and prior lab trials. A very good correspondence was observed, which enabled us to affirmatively predict the significant reduction of SO_x in a full-scale (Fig.6), on-board system operating with HFO.

Table 1: Removal Efficiencies of the NO and NO_x

En. load	%	0	50	100
Ox.conc.	mg/l	0	1	3,3
Gas flow r.	Nm^3/h	3316	4751	4915
Gas t. inlet	°C	51	136	124
Dose	kGy	4,1	5,7	5,5
Inlet conc.	NO ppm	95	252	298
	NO_x ppm	110	271	317
Rem. rate	NO %	81,8	57,4	65,2
	NO_x %	38,8	38,0	45,8

The NO_x removal was examined for different engine loads and different concentrations of oxidant.

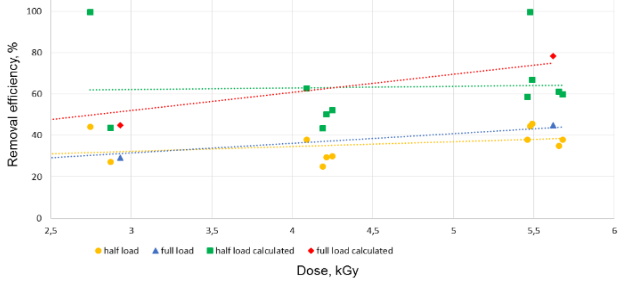

Figure 4. Dose dependence of NO_x removal efficiency for 50% and100 % engine load.

The increase of oxidant concentration in the process water in the scrubber has a strong positive impact on NO_x removal efficiency (Fig.5).

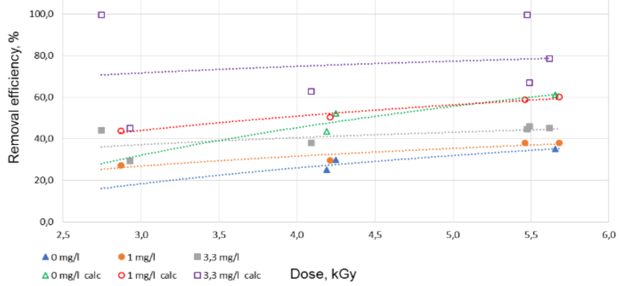

Figure 5. Dose dependence of NO_x removal efficiency for different concentrations of oxidant.

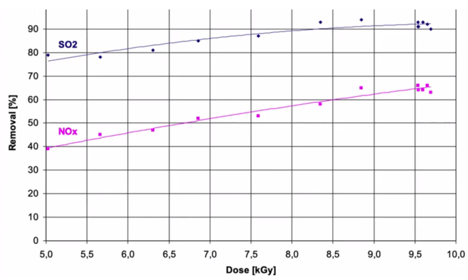

Figure 6. Dose dependence of SO_2 and NO_x matched with previous laboratory tests.

Way forward. Based on the promising results of the PoC project and with the great support of the stakeholders, maritime and accelerator partners, the initial Collaboration has been considerably enlarged. The partners are keen to pursue further developments of the hybrid technology and *inter alia* have prepared the *Hybrid Exhaust-gas-cleaning Retrofit Technology for International Shipping* – HERTIS project [30] proposal. This is an unprecedented, multi-disciplinary undertaking, linking together the maritime and particle accelerator communities under the umbrella of scientific research: it is a joint endeavour of 12 partners from 8 European countries. Enhancing Collaboration with the following: University of Tartu; the major shipping industry players include Grimaldi Group, the American Bureau of Shipping and Ecospray; the economical feasibility and business case are to be impartially evaluated by business experts KPMG; the environmental impact assessment expertise and objectiveness was conducted by Western Norway Research Institute.

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Organic pollutant removal from marine diesel engine off-gases under electron beam and hybrid electron beam and wet scrubbing process

Yongxia Sun[1, *], Andrzej G. Chmielewski[1], Andrzej Pawelec[1], Gösta Mattausch[2], Toms Torims[3]

[1] Institute of Nuclear Chemistry and Technology, Poland. y.sun@ichtj.waw.pl

[2] Fraunhofer Institute for Organic Electronics, Electron Beam and Plasma Technology, FEP, Germany.

[3] Riga Technical University, Latvia.

Abstract

Organic pollutant removal from ship emission was studied using two processes, electron beam and hybrid electron beam and wet scrubbing process. A mobile accelerator unit was applied to treat 4915 Nm^3/h of flue gas emitted from a tugboat in Riga Shipyard. 3m^3 sea water containing 36.8 mM of $NaClO_2$ oxidant was used as a wet scrubber solution. Organic pollutants, mainly VOCs, were collected at 3 different sampling points, before and after irradiation vessels, and after wet-scrubber unit, respectively. They were collected with glass sampling bottles, tedlar bags, Coconut Shell Charcoal sorbents and XAD-2 sorbents. CH_3OH and CH_3OH/CH_2Cl_2 (1:1) were used to extracted VOCs from CSC and XAD-2 sorbents, respectively. Syringe filters were used to obtain the solid-free extraction solutions. They were concentrated using a micro-extractor under continuously blowing high-purity Ar. A gas chromatography–mass spectrometry was used for analysis. The identified organic compounds were: aliphatic hydrocarbons (Dodecane $C_{12}H_{26}$ to Eicosane $C_{20}H_{42}$), aromatic hydrocarbon (toluene), esters ($C_3H_7COOCH_3$, $(C_4H_9OCO)_2C_6H_4$), nitro compounds ($C_3H_5NO_3$, $C_4H_7NO_2$), acid ($C_7H_{15}COOH$). After 4.2 kGy EB irradiation, around 50% -100% aliphatic hydrocarbons, 83% toluene, 7.5% $(C_4H_9OCO)_2C_6H_4$ were removed from the off-gases, after EB hybrid wet-scrubber process, most organic compounds including nitro compounds were removed , only trace amount of toluene, hexadecane , octadecane and dibutyl phthalate were present in the gas phase.

Keywords: organic pollutants, VOC, electron beam, wet scrubber, off-gases, marine diesel engine

1. Introduction

Combination of SO_2 , NOx and volatile organic pollutants (VOCs) emission from marine diesel engine off-gases caused serious problem to the environment and human health. Some VOCs are ozone-depleting substances in stratosphere, ozone formation in troposphere and precursor for secondary aerosol formation. Some VOCs have direct adverse effect on human health. According to US EPA Clean Air Act, 187 hazardous air pollutants were listed [1], including toluene. The strict regulation concerning SO_2 and NOx emission from ship emission has been enacted accordingly. Based on MARPOL air pollution Annex VI, sulphur emission from ship exhaust gas can't exceed 0.1% (wt/wt) sulphur content in sulphur emission control areas (SECA), 0.5% sulphur content limits in global marine area. Limits of NOx emission has been put into force in North America since June 20, 2019, between 3.4 and 2g/kWh depending on the engine speed based on TIER III requirement [2].

Heavy fuel oil (HFO), due to its low cost, is a main energy source for marine industry. However, high concentration of SO_2, NOx is emitted during combustion of HFO , and organic pollutants are also generated . To reduce SO_2 emission, wet scrubbing method is commonly used to scavenge SO_2 from off-gases emitted from the ship engines and boilers. To reduce NOx emission, mainly catalyst reduction method is applied [3]. A process of electron beam (EB) hybrid with wet-scrubbing is a process to remove SO_2 and NOx simultaneously from marine engine off-gases, it was initially studied in the laboratory scale in the Institute of Nuclear Chemistry and Technology (INCT) [4], then tested in a real maritime environment in Riga Shipyard within the ARIES proof-of-concept project. It was the first pilot plant test in the world and in the real maritime conditions. This pilot plant set-up and results of SO_2 and NOx removal have been described in details [5]. During the pilot test for SO_2 and NOx removal from ship emission, organic pollutants before and after treatment were sampled and collected. They were transported to INCT laboratory for analysis. Subsequently organic pollutant removal under EB and EB hybrid wet-scrubbing process was studied. This paper contains the initial test results for the organic pollutant removal.

2. Experimental set-up and analysis of the samples

2.1 Organic pollutant sampling system

Flue gas was generated from a tugboat “Orkans” equipped with two two-stroke diesel engines in Riga Shipyard. Sulfur-free fuel was used. Flue gas compositions were measured in three

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main points of facility: at the inlet to the irradiation unit, at the outlet after irradiation unit and at the outlet of the plant after wet-scrubbing treatment. Two different types of flue gas analyzers were used: Kane Quintox flue gas analyzer (Kane Int. Limited, UK) at the inlet and outlet of the treatment plant and Land Lancom series II portable gas analyzer (AMETEK Land, United Kingdom) after the irradiation unit. Concentration of the following elements of gas composition were determined by flue gas analyzers: sulfur dioxide (SO_2), nitrogen monoxide (NO), nitrogen dioxide (NO_2), oxygen (O_2), carbon dioxide (CO_2), carbon monoxide (CO), and hydrocarbons (CxHy). The temperature of flue gas before irradiation, after irradiation and after wet-scrubbing treatment was 133°C , 85°C and 34°C respectively. It was measured by means of thermocouples type K manufactured by Czaki (Poland). Flue gas velocity was measured by Testo 452 anemometer produced by Testo, Germany.

4915Nm^3/h of flue gas emitted from tugboat "Orkāns" was treated deploying a mobile accelerator unit WESENITZ-II [5]. 3 m^3 sea water containing 3.3 g/dm^3 $NaClO_2$ oxidant was used as a wet scrubber solution. Temperature of the scrubbing solution increased from 27°C to 29°C after scrubbing flue gas. Organic pollutants' removal from ship emissions have been studied under two processes, EB and EB hybrid wet scrubbing process. The residence time of flue gas in the irradiation zone and the wet-scrubber was 0.112 s and 2.2 s , respectively. Gaseous organic pollutants , mainly VOCs, were collected at three different sampling points: before irradiation vessel, after irradiation vessels, and after wet-scrubber unit (Figure 1) . They were collected with glass sampling bottles, tedlar bags, Coconut Shell Charcoal (CSC) sorbents (SKC Inc, USA) and XAD-2 sorbents (SKC Inc, USA) according to US EPA method 18 [6], a scheme of the sampling system was presented in Figure 2.

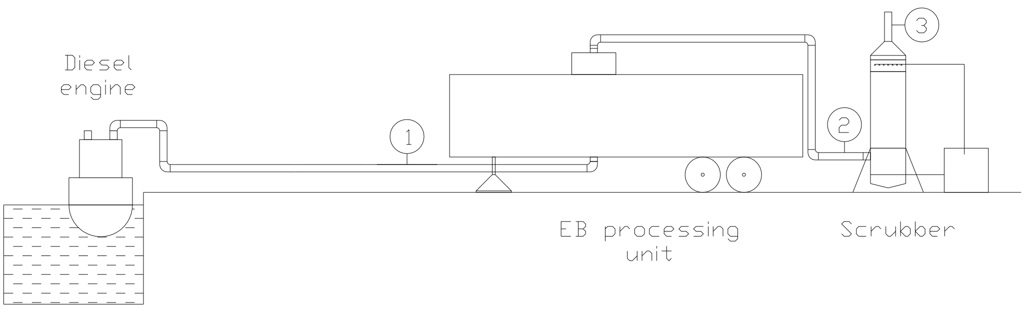

Figure 1. The sampling points of the organic pollutants

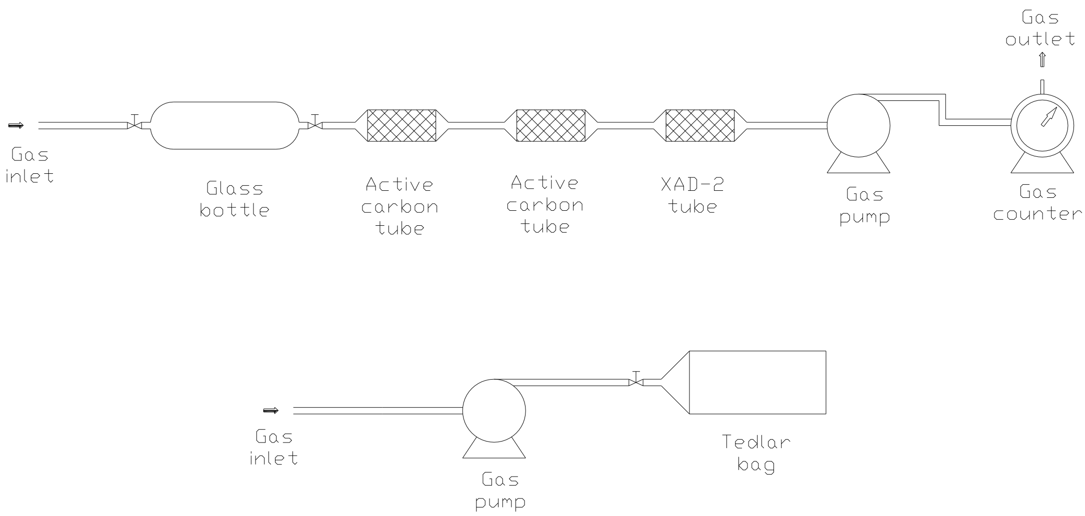

Figure 2. A scheme of the sampling system

2.2 Methodology of the analysis

Two main factors influence on flue gas composition, fuel and combustion condition. In this pilot test, composition of flue gas emitted from diesel engine consists of SO_2, NOx, CO, CO_2, particulate matter (PM), hydrocarbons etc. similar to the composition of flue gas emitted from heavy fuel combustion [7]. SO_2, NOx, CO, CO_2, O_2 and total hydrocarbons were directly measured with portable flue gas analyzers. For gaseous organic pollutants, glass sampling bottles and tedlar bags were used to collect very volatile compounds with high concentration. For low concentration compounds, adsorbents were used to concentrate the sample, thus lowering the detection limit of these compounds [6]. A GCMS-QP5050 (Shimadzu company, Japan) analyzer was used for analysis. Standard solutions, such as: AK-102.0-NAS-10X standard , M-502-REG and AK-101AA-ARO standard were used for making calibration curves. All these standard solutions were ordered from AccuStandard company, USA. For the off-gases sampled using Tedlar bags and glass bottles, 500 microliter sampling gas was directly injected into the GC-MS analyzer. For the off-gases adsorbed by the sorbents, 10 ml CH_3OH (HPLC purity) and CH_3OH/CH_2Cl_2 (1:1, HPLC purity) were used to extracted VOCs from CSC and XAD-2 sorbents, respectively. The solid-free extraction solutions were obtained by using syringe filters to separate extraction solution from sorbents. They were concentrated to 0.2 ml using a micro-extractor under continuously blowing high-purity Ar (Argon-X5OS PRM, air products, Poland) . 1 µl concentrated solution was injected into the GC-MS for analysis. HP- 5MS column (30m × 0.25mm ID × 25 µm, Agilent J&W, USA) was used. The analytical condition of GC-MS was : 40°C hold for 1 minute, increased to 60°C at 1°C/min., then increased to 280°C at 5°C/min, column flow was 1.2 ml/min, split ratio was 100:1 when liquid sample was injected. Injection temperature was 250°C; Interface temperature was 280°C. solvent cutting time was 2 minutes. Electron ionization was applied, Wiley library was used for reference mass spectra.

3. Results and discussion

3.1 Direct analysis of VOCs collected in glass bottle

Off-gases (or flue gas) before and after treatment (EB or EB with scrubber) collected with glass sampling bottles and Tedlar bags was directly analyzed. A GC-MS spectrum of off-gases before irradiation is shown in Fig. 3. 7 unidentified peaks (due to the lack of standards or database of reference mass spectra in the library) were recorded in the flue gas. After EB or EB combined with the wet scrubber treatment, no peak was detected.

Figure 3. A GC-MS spectrum of the flue gas before irradiation

3.2 Analysis of VOCs collected in the CSC sorbents

CSC and XAD-2 sorbents were used to collect the flue gas samples before and after treatment. A total amount of 106 L, 68 L and 112 L of flue gas was sampled at the three different sampling points (before EB, after EB, after EB with scrubber), respectively. The results are presented in Figure 4 (4a: before treatment; 4b: after EB; 4c: after EB and scrubber). Table 1 lists organic compounds, which were identified by the GC-MS analyzer, eluting at different retention time (RT) . Note "+" in Table 1 means organic compounds detected by the GC-MS analyzer ; and note "-" means organic compounds below detection limit. From Figure 4a and Table 1, it is seen that the identified organic compounds from ship emission include: nitro compounds (Nitropropanone, 3-nitro-1-Butene), esters (Methyl butyrate, Butoxyethoxyethyl acetate, (Hexadecanoic acid, methyl ester), Dibutyl phthalate, (Octadecanoic acid, methyl ester)), aliphatic hydrocarbons (C_xH_{2x+2}, x=12, 15-18, 20-21), toluene and chlorotoluene. After EB treatment (see figure 4b) , most organic compounds have been removed from flue gas. Chlorotoluene and nitro compounds have been removed completely from gas phase, however some aliphatic compounds (dodecane, hexadecane and octadecane) with high concentration (refer Table 3) still exist in the gas phase, Butoxyethoxyethyl acetate and Dibutyl phthalate were still detected by the GC-MS analyzer. After EB and wet scrubber treatment (see figure 4c) , only toluene, hexadecane , octadecane and dibutyl phthalate were present in the gas phase, other organic compounds have been removed.

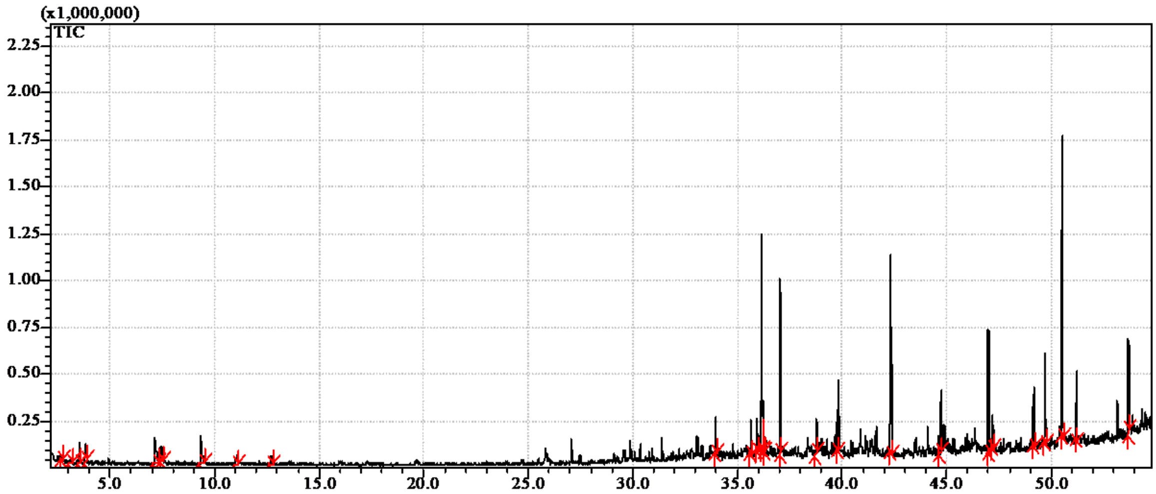

Figure 4a. A GC-MS spectrum of flue gas collected with the CSC sorbents before EB irradiation

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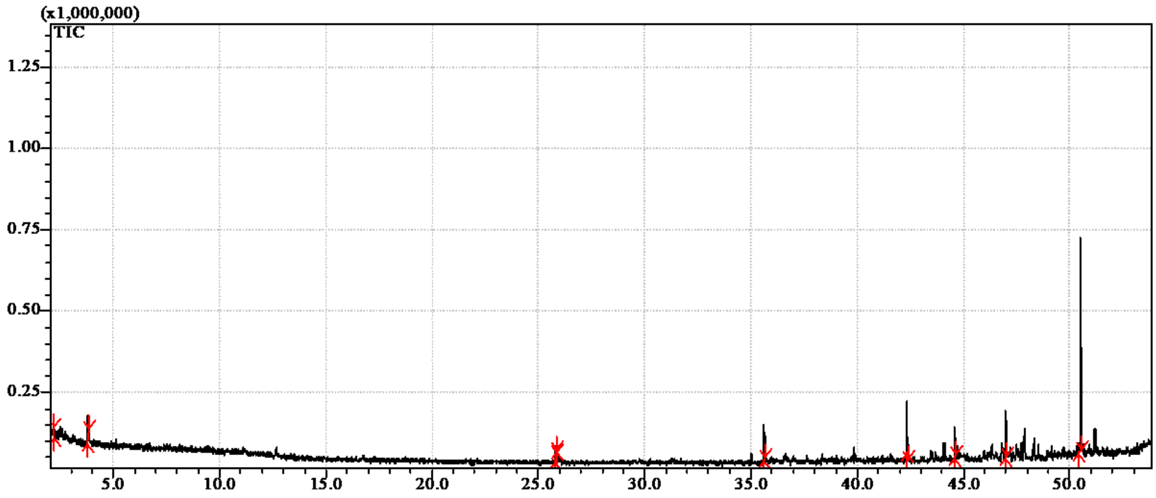

Figure 4b. A GC-MS spectrum of flue gas collected with the CSC sorbents after EB irradiation

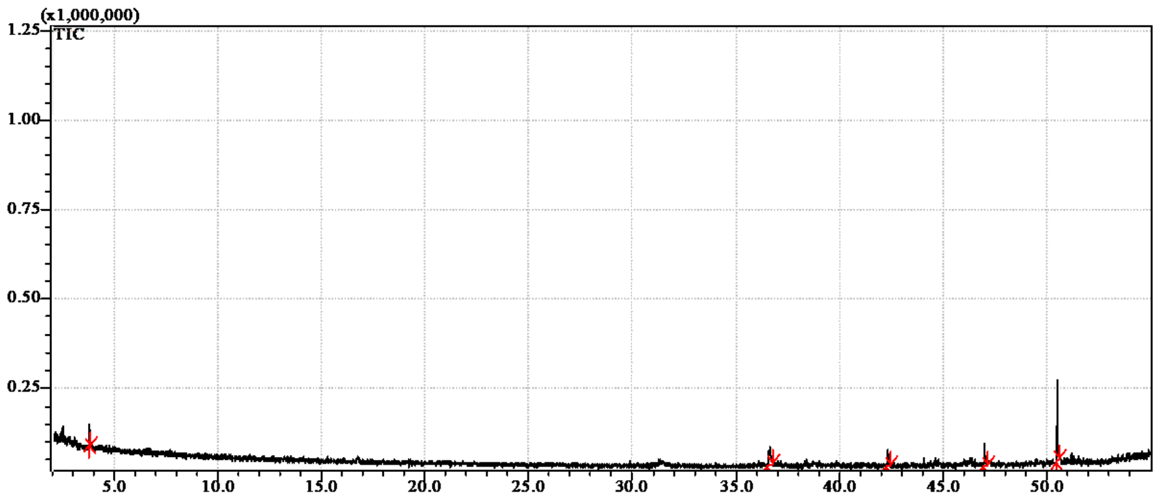

Figure 4c. A GC-MS spectrum of flue gas collected with the CSC sorbents after EB with wet scrubber treatment

Table 1. List of organic compounds eluting at different retention time (RT) of the GC-MS spectrums presented in Figure 4

RT(min.)	Compound	ship emission	after EB	after EB with wet scrubber
3.833	Toluene	+	+	+
7.142	Nitropropanone, $C_3H_5NO_3$, $CH_3COCH_2NO_2$	+	-	-
7.442	1-Butene, 3-nitro-, $C_4H_7NO_2$, $CH_2=CHCH(CH_3)NO_2$	+	-	-
11.042	Methyl butyrate, $C_5H_{10}O_2$, $C_3H_7COOCH_3$	+	-	-
12.700	Chlorotoluene, C_7H_7Cl	+	-	-
36.156	Butoxyethoxyethyl acetate, $C_{10}H_{20}O_4$, $CH_3COO(C_2H_4O)_2C_4H_9$	+	+	-
37.039	Dodecane, $C_{12}H_{26}$	+	+	-
39.798	Pentadecane, $C_{15}H_{32}$	+	-	-
42.351	Hexadecane, $C_{16}H_{34}$	+	+	+
44.739	Heptadecane, $C_{17}H_{34}$	+	-	-
47.004	Octadecane, $C_{18}H_{38}$	+	+	+
47.212	Hexadecane, 2,6,10,14-tetramethyl-, $C_{20}H_{42}$	+	-	-
49.152	n-Eicosane, $C_{20}H_{42}$	+	-	-
49.717	Hexadecanoic acid, methyl ester, $C_{17}H_{34}O_2$	+	-	-
50.519	Dibutyl phthalate, $C_{16}H_{22}O_4$, $C_6H_4(COOC_4H_9)_2$	+	+	+
51.208	Heneicosane, $C_{21}H_{44}$	+	-	-
53.701	Octadecanoic acid, methyl ester, $C_{19}H_{38}O_2$	+	-	-

3.3 VOCs collected in the XAD-2 sorbent

In order to capture other organic pollutants which were not effectively adsorbed by Coconut Shell Charcoal sorbents from flue gas, XAD-2 sorbent was connected after the CSC sorbents. Analytical results of the GC-MS were presented in Figure 5 and Table 2. It is seen that 2,2-dimethoxypropane, methyl octanoate, octanoic acid and toluene were detected in the flue gas from ship emission (see Figure 5a and Table 2) . After EB treatment (Figure 5b), 2,2-Dimethoxypropane (RT= 2.184 min.) and methyl octanoate (RT= 31.208) were removed from flue gas. After EB with wet scrubber treatment, only toluene (RT= 3.817 min) was present in the flue gas.

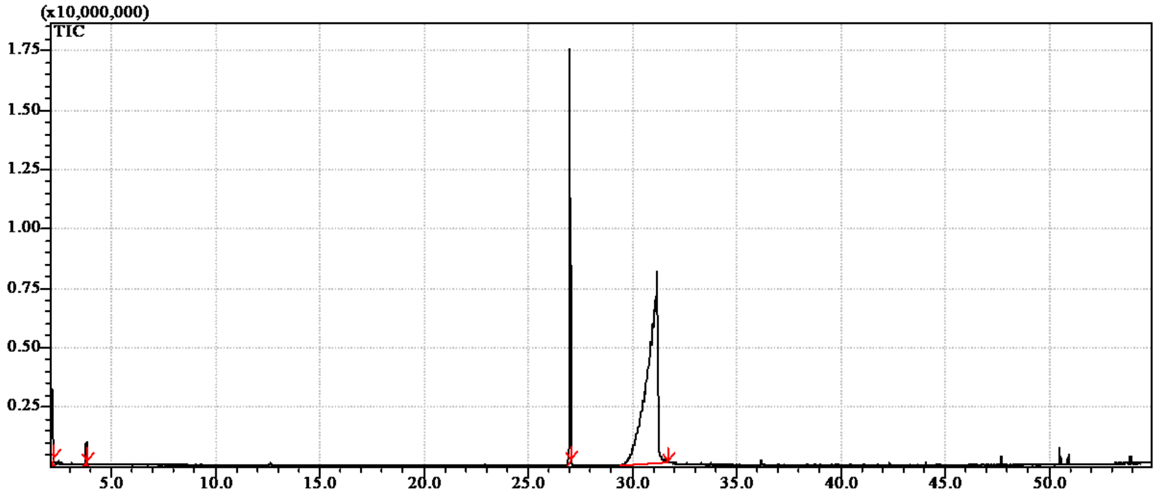

Figure 5a. A GC-MS spectrum of flue gas collected with the XAD-2 sorbents before EB irradiation

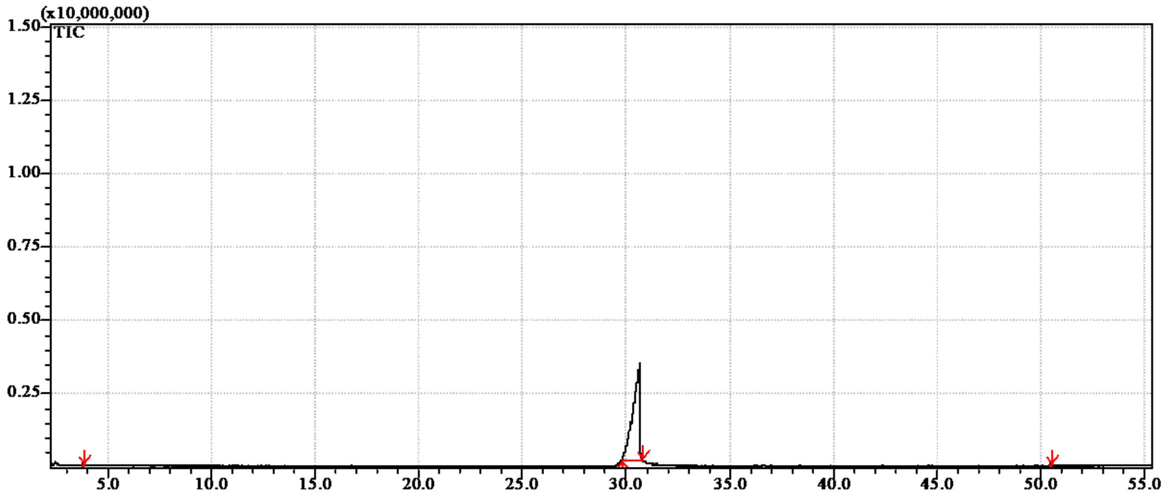

Figure 5b. A GC-MS spectrum of flue gas collected with the XAD-2 sorbents after EB irradiation

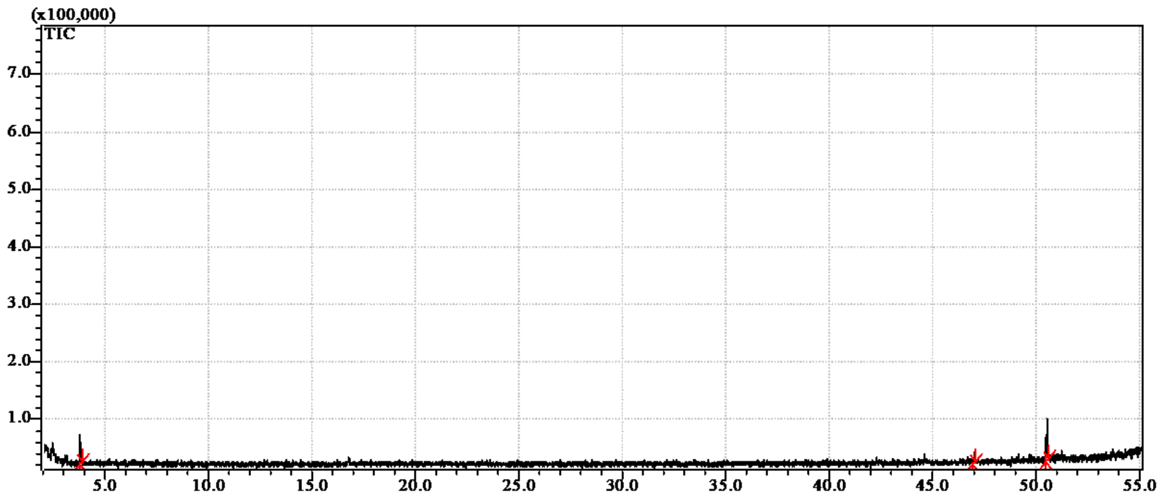

Figure 5c. A GC-MS spectrum of flue gas collected with the XAD-2 sorbents after EB with wet scrubber treatment

Table 2. List of the organic compounds eluting at different retention time (RT) of the GC-MS spectrums presented in Figure 5

RT(min.)	Compound Name	ship emission	after EB	after EB with wet scrubber
2.184	2,2-Dimethoxypropane, $C_5H_{12}O_2$, $(CH_3O)_2$-C-$(CH_3)_2$	+	-	-
3.817	Toluene, C_7H_8	+	+	+
27.001	Methyl octanoate, $C_7H_{15}COOCH_3$	+	-	-
31.208	Octanoic Acid, $C_7H_{15}COOH$	+	+	-

3.4 Removal efficiency of organic compounds

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We summarized the analytical results obtained from CSC and XAD-2 sorbents, the removal efficiency of the organic pollutants after EB and EB with wet scrubber process were presented and listed in Table 3. For these organic compounds which we had standard solutions for making calibration curve, their concentrations were given in Table 3. For others organic compounds, only removal efficiency was given based on their area counting given by the GC spectrum. It is seen that in the flue gas from ship emission, toluene concentration was relatively high, around 1.04 mg/m^3. Concentration of aliphatic hydrocarbons varies from 9.60 $\mu g/m^3$ (n-Eicosane) to 57.96 $\mu g/m^3$ (Hexadecane). After EB treatment, most VOCs were removed from gas phase. Degradation efficiency for aliphatic hydrocarbons, the compounds with lower carbon chain have higher removal efficiency , 79.59% for dodecane and 48.57% for octadecane. Removal efficiencies of butoxyethoxyethyl and octanoic acid were 89.7% and 57.8%, respectively. However only 7.5% Dibutyl phthalate was removed from flue gas after EB treatment . Eicosane and heneicosane were not detected after EB treatment due to their very low concentration in the flue gas. For those compounds with relatively high concentration, e.g., toluene, hexadecane , octadecane and dibutyl phthalate, after EB with wet- scrubbing process, their removal efficiency greatly increased comparing with sole EB treatment, from 70.8% to 83.2% for toluene, 54.71% to 97.79% for hexadecane , 48.57% to 92.01% for octadecane , and from 7.50% to 86.3% for dibutyl phthalate. Toluene concentration in flue gas decreased from 1.04 mg/m^3 (ship emission) to 0.175 mg/m^3after EB with wet-scrubbing process.

Table 3. List of removal efficiency of organic compounds after EB and EB with wet-scrubber process

Compound	Ship emission	Removal efficiency (after EB)	Removal efficiency (after EB with wet scrubber)	PEL*[8] (mg/m^3)
Toluene	1.04 mg/m^3	70.8% (0.304mg/m^3)	83.2% (0.175 mg/m^3)	37
Nitropropanone, $C_3H_5NO_3$, $CH_3COCH_2NO_2$	+	100%	100%	
1-Butene, 3-nitro-, $C_4H_7NO_2$, $CH_2{=}CHCH(CH_3)NO_2$	+	100%	100%	
Methyl butyrate, $C_5H_{10}O_2$, $C_3H_7COOCH_3$	+	100%	100%	

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Chlorotoluene, C_7H_7Cl	+	100%	100%	250
Butoxyethoxyethyl acetate, $C_{10}H_{20}O_4$	+	89.7%	100%	
Dodecane, $C_{12}H_{26}$	30.63 µg/m^3 (0.004 ppm)	79.59% (6.25 µg/m^3)	100%	
Pentadecane, $C_{15}H_{32}$	10.13 µg/m^3	100%	100%	
Hexadecane, $C_{16}H_{34}$	57.96 µg/m^3 (0.006 ppm)	54.71% (26.25 µg/m^3)	97.79% (1.28 µg/m^3, 0.13 ppb)	
Heptadecane, $C_{17}H_{34}$	10.72 µg/m^3	100%	100%	
Octadecane, $C_{18}H_{38}$	38.05 µg/m^3 (0.003 ppm)	48.57% (19.57 µg/m^3)	92.01% (3.04 µg/m^3, 0.24 ppb)	
Hexadecane, 2,6,10,14-tetramethyl-, $C_{20}H_{42}$	+	100%	100%	
n-Eicosane, $C_{20}H_{42}$	9.60 µg/m^3	100%	100%	
Hexadecanoic acid, methyl ester, $C_{17}H_{34}O_2$	+	100%	100%	
Dibutyl phthalate, $C_{16}H_{22}O_4$, $C_6H_4(COOC_4H_9)_2$	+	7.50%	86.3%	5
Heneicosane, $C_{21}H_{44}$	13.31 µg/m^3	100%	100%	
Octadecanoic acid, methyl ester, $C_{19}H_{38}O_2$	+	100%	100%	
2,2-Dimethoxypropane, $(CH_3O)_2$-C-$(CH_3)_2$	+	100%	100%	
Methyl octanoate, $C_7H_{15}COOCH_3$	+	100%	100%	
Octanoic Acid, $C_7H_{15}COOH$	+	57.8%	100%	

Note: *PEL: Permissible exposure limits.

4. Conclusions

Pilot test in Riga shipyard shows that after 4.2 kGy EB irradiation, most organic pollutants have been removed from flue gas. Chlorotoluene and nitro compounds have been removed completely from gas phase, some aliphatic compounds (dodecane, hexadecane and octadecane) with high concentration still exist in the gas phase, their removal efficiency varies from 79.59% for dodecane and 48.57% for octadecane. After EB and wet scrubber treatment, most organic pollutants have been removed completely from flue gas , only trace amount of toluene (0.175 mg/m^3), hexadecane (0.13 ppb) , octadecane (0.24 ppb) and dibutyl phthalate were present in the gas phase . Their removal efficiency might be further increased by increasing irradiation dose, increasing liquid/gas ratio and residence time of flue gas in the wet-scrubber, increasing temperature of the scrubber solution. Successful ARIES proof-of-concept tests in Riga Shipyard have demonstrated results which are opening opportunity for the further on board tests and application of the technology on board of the sea-going ships on regular routes within the HERTIS Collaboration.

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TECHNICAL REPORT

Plasma technology to remove NO_x from off-gases

A. Pawelec*[1], A. G. Chmielewski[1], Y. Sun[1], S. Bułka[1], T. Torims[2], G. Pikurs[2], G. Mattausch[3]

[1]Institute of Nuclear Chemistry and Technology, Dorodna 16, 03-195 Warsaw, Poland

[2]Riga Technical University, Riga, Latvia

[3]Fraunhofer Institute for Organic Electronics, Electron Beam and Plasma Technology

FEP, Dresden, Germany

* corresponding author, e-mail: a.pawelec@ichtj.waw.pl

Abstract

Operation of marine diesel engines causes significant emission of sulphur and nitrogen oxides, that is a serious problem especially in harbour areas and the main sea routs. It was noticed worldwide and the regulations concerning harmful emissions were introduced. There were several solutions elaborated, however emission control for both, SO_x and NO_x requires two distinctive processes realized in two separated devices, that is problematic due to limited space on board of the ship and high overall costs. Therefore, the electron beam flue gas treatment process was adopted to the abatement of the marine diesel off-gases. This novel solution combines two main processes: first the flue gas is irradiated with electron beam where NO and SO_2 are enriched to higher oxides; second stage is wet scrubbing to remove both pollutants with high efficiency.

Laboratory tests showed that said hybrid technological process could be effectively applied to remove SO_2 and NOx from diesel engine off-gases. Different compositions of absorbing solution with three different oxidants (NaClO, $NaClO_2$ and $NaClO_3$) were tested. The highest

NO_x removal efficiency (>96%) was obtained when sea water-$NaClO_2$-NaOH was used as scrubber solution at 10.9 kGy dose. The process was further tested during the proof-of-concept project, in real maritime conditions at Riga shipyard, Latvia. More than 45% NO_x was removed at 5.5 kGy dose for 4800 Nm^3/h off-gases from ship emission. The operation of the plant was the first case of examination of the hybrid electron beam technology in the real conditions. Taking in account the experiment conditions and available accelerator irradiation chamber geometry, good agreement was obtained with laboratory tests. The results obtained in Riga shipyard provided very valuable information for this technology application for control of large cargo ship emission.

Keywords: marine diesel engines, flue gas treatment, SO_x, NO_x, electron beam, ship emissions

1. Introduction

According to literature data [1] sea transport is responsible for 15% of global emission of nitrogen oxides and 5 – 8% of global emission of sulphur oxides. This problem is of great importance because 70 percent of sea transport emission is generated not longer than 400 kilometers from the land. For better understanding of the magnitude of sulphur and nitrogen oxides emission it is worth to notice, that in 2000 the emission around Europe (area of Baltic Sea, North Sea, north east part of Atlantic, Mediterranean Sea and Black sea) of the pollutants was estimated at 2.3 million tons of SO_2, 3.3 million tons of NO_x and 250 thousand tons of particles. It is supposed, that in 2020 such numbers shall be 40 – 50% greater [2].

The problem was noticed worldwide and the regulations concerning SO_2 and NO_x emissions were introduced. The most important are International Maritime Organization (IMO) ship pollution rules known as MARPOL convention. According to Annex VI of the convention

SO_2 emissions shall be reduced to 2 g/kWh that corresponds with 0.5% sulphur content in fuel. In Sulphur Emission Control Areas – (SECAs) such emission is limited to 0.4 g/kWh in, that corresponds with 0.1% [3]. For comparison typical sulphur content in heavy fuel oil used in marine engines is about 3% that means 12 g/kWh emission level.

In the case of nitrogen oxides the emissions are also strictly limited. According to MARPOL convention NO_x emission standards depend on ship production date and rotation speed of engine and for new constructed ships (after 2016) varies from 2.0 to 3.4 g/kWh, that means that emission reduction at the level of 80 % is required [4].

There are several solutions to ensure compliance: application of the low sulphur fuels (marine diesel), switching to LNG [5] or instalment of the sea water scrubbing systems [6] for SO_2 emission control. In the case of NO_x fuel combustion process modification (engine modification) [7] or selective catalytic reduction (SCR) process are used [8]. All of these processes have their inherited limitations. Low sulphur fuel may be harmful for older engines and is much more expensive than regular marine diesel fuel. Similarly, combustion process modification has limited NO_x emission reduction efficiency. Therefore, today the most popular solution in marine industry is combination of sea water scrubbing, for SO_2 and SCR for NO_x emission control. However, these are two distinctive processes realized in two separate devices and require application of the specific process parameters (e.g. temperature) as well as costly control and maintenance solutions.

In this case electron beam flue gas treatment (EBFGT) technology allowing for simultaneous removal of both pollutants in one process may be an alternative. The technology was already applied in the power industry and further research on its development has been carried on in the Institute of Nuclear Chemistry and Technology (INCT). During the research carried on in the Institute, the process was adopted in-lab to the marine diesel flue gases treatment conditions.

In this novel technology, called hybrid electron beam flue gas treatment process, two main processes were combined. In the first step flue gasses are irradiated for oxidation of NO and SO_2 to higher oxides, while in the second step the pollutants are being absorbed into aqueous solution by wet scrubbing process. It allows simultaneous removal of both SO_x and NO_x with high efficiency. The idea of the process is presented in Figure 1.

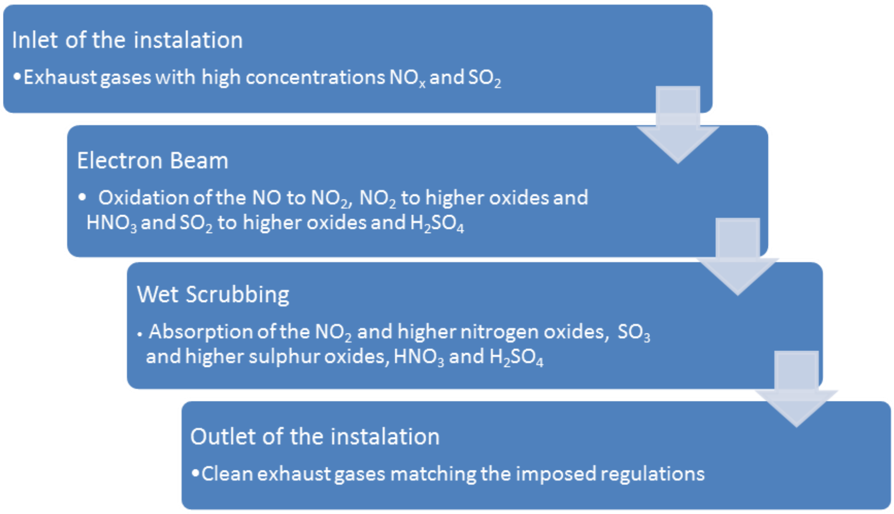

Figure 1. The concept of hybrid electron beam flue gas treatment process.

3. Laboratory tests

First stage of the research on hybrid electron beam technology was conducted in the laboratory of the INCT in batch mode. During this research several scrubbing solutions as 3.5% sodium chloride (simulated seawater), sodium hydroxide solution or simulated seawater with oxidant addition were applied. The highest efficiency of NO_x removal (89.6%) was obtained in combined electron beam – wet scrubbing process where simulated seawater and $NaClO_2$ with phosphate buffer was applied as scrubbing solution [9]. A comparison of process efficiencies between method of sole electron beam and a hybrid technology, coupling electron beam with a wet scrubber in two cases: with simulated sea water and with simulated sea water and $NaClO_2$ addition with phosphate buffer is presented in Figure 2.

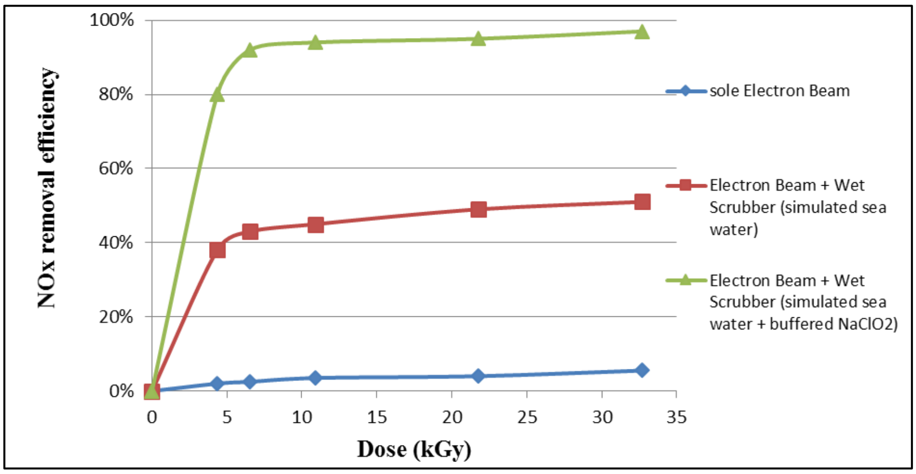

Figure 2. Comparison of process efficiencies between sole electron beam and hybrid electron beam process with simulated sea water and simulated sea water and $NaClO_2$ addition with phosphate buffer [9].

As the application of oxidants results in remarkable increase of NOx removal efficiency in hybrid electron beam flue gas treatment process, several oxidants (NaClO, $NaClO_2$ and $NaClO_3$) were examined. The most promising results were achieved when sodium chlorite ($NaClO_2$) buffered with phosphate buffer (Na_2HPO_4-KH_2PO_4) was applied [10]. The results of the research are presented in Figure 3.

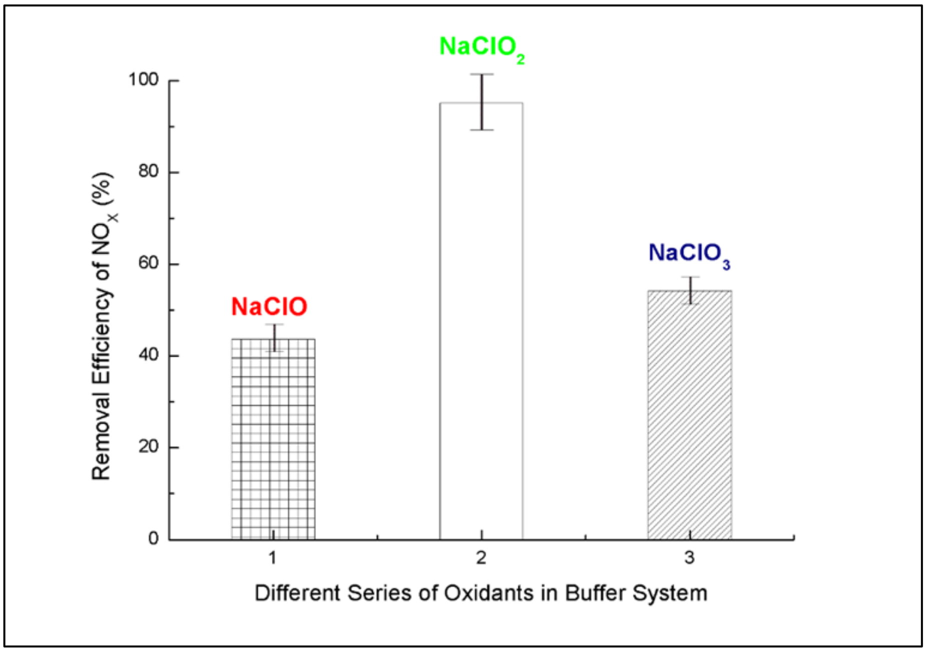

Figure 3. Comparison of hybrid electron beam – wet scrubber process with the addition of different oxidants in the seawater buffered with phosphate buffer solution [10].

The research were continued with use of large laboratory scale installation (Figure 4). operated in continuous mode. 3.5% sodium chloride solution as simulated seawater with addition of 10 mM sodium chlorite as oxidizing agent was applied in these tests, however instead of phosphate buffer sodium hydroxide was used. pH of the scrubbing solution was controlled by pH-meter and kept over 7.5, that is natural pH of seawater.

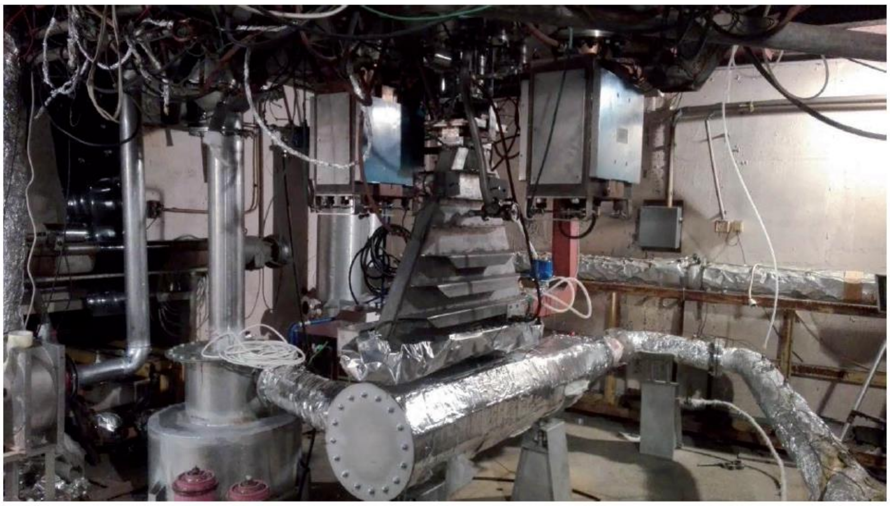

Figure 4. Photo of EBFGT pilot laboratory flow system. Wet scrubber (left) and process vessel (right) under ILU 6 electron accelerator scanning horn.

The obtained NO_x removal efficiencies were about 90% for 10.9 kGy dose. During the experiments it was noticed, that spraying some amount of scrubbing solution inside reaction chamber may remarkably increase NO_x removal efficiency. The obtained result for 10.9 kGy dose was as high as 97% (Figure 5).

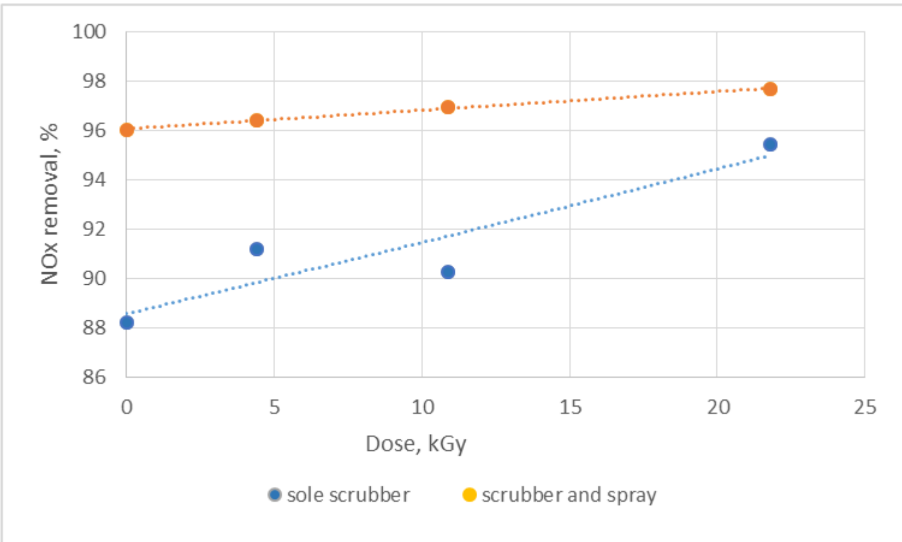

Figure 5. NO_x removal efficiency in hybrid electron beam wet scrubbing system with and without scrubbing solution spraying inside reaction chamber (3.5% NaCl-NaOH-10 mM $NaClO_2$ as scrubbing solution SO_2: 716 ppm; NOx: 2263 ppm).

4. Proof-of-concept tests in real marine environment

Field scale tests (on shore) were realized in the frame of the project "PoC Development of hybrid electron accelerator system for the treatment of marine diesel exhaust gases" (ARIES) [11]. The main goal of this project was to demonstrate hybrid electron beam flue gas treatment technology for efficient removal of SO_2 and NO_x from marine diesel engine flue gases. The project was realized in Riga Shipyard (Latvia) in international cooperation between Riga Technical University, Center of High Energy Physics and Accelerator Technologies – RTU (Riga, Latvia), Institute of Nuclear Chemistry and Technology – INCT (Warsaw, Poland), The European Organization for Nuclear Research – CERN (Geneva, Switzerland), Fraunhofer Institute for Organic Electronics, Electron Beam and Plasma Technology – FEP (Dresden, Germany), Remontowa Marine Design – Remontowa (Gdansk, Poland), Milgravja Tehnoloģiskais Parks - Riga Shipyard – RKB (Riga, Latvia) and BIOPOLINEX Sp. z o.o. (Lublin, Poland).

Pilot hybrid electron beam marine flue gas treatment facility located in Riga Shipyard consisted of the following units:

- flue gas ship diesel engine,
- mobile electron beam unit,
- seawater scrubbing unit,
- scrubbing solution closed loop system,
- measurement and monitoring system.

The general scheme of the pilot plant is presented in Figure 6 and photo of the system in Figure 7.

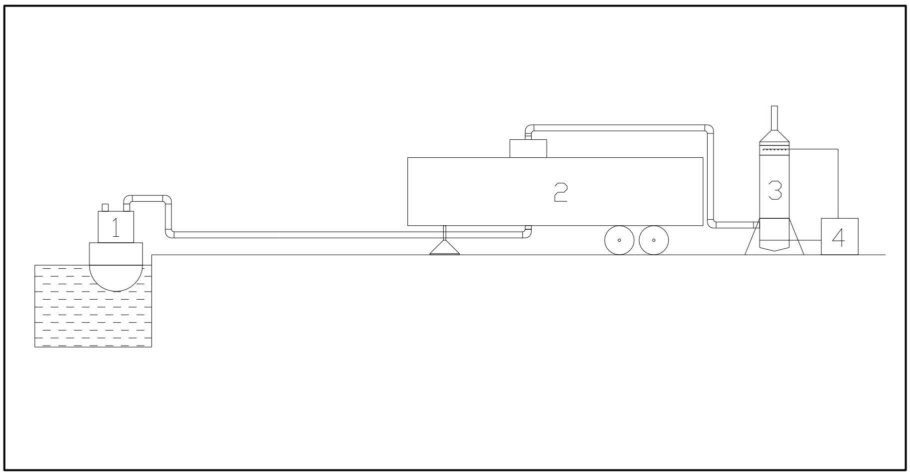

Figure 6. General scheme of pilot hybrid electron beam flue gas treatment plant.

1 – flue gas source, 2 - mobile accelerator, 3 – scrubber, 4 – seawater tank

A tugboat “Orkāns” of Riga Shipyard, equipped with double two-stroke 450kW diesel engines of, berthed at the pier, was used as the source of flue gas. Outlet of gas pipe of one of the engines was flexibly connected to irradiation device by 320 mm steel pipe.

A mobile accelerator manufactured by Fraunhofer FEP, Germany was used as an irradiation device. This device was originally designed for seed irradiation and was adopted to flue gas processing for the purposes this project. Irradiation chamber of rectangular cross section (120 x 1560 mm) and 1180 mm height was applied. Gas flowed vertically from bottom to top direction and was irradiated from both sides by two 125 kV accelerators of 100 mA beam current.

Seawater scrubbing was realized in counter-current, packed scrubber. The device diameter was 1.2 m and its height was 5.5 m. Scrubber was filled with Bialecki rings, filling height was 2.6 m. A closed loop system was applied for seawater circulation in the scrubber. Two tanks filled with 3 m^3 of seawater were used as a scrubbing solution storage in the closed loop system. The water from the tanks was filtered and pumped to a system of nozzles located at the top of the scrubber and sprayed at the top of the filling, then flowed to the bottom of the device and back to the tanks by gravity. The gas from the irradiation unit was directed to the lower part of the scrubber and was released to the atmosphere by a stack located at the top of the device.

Figure 7. Photo of EBFGT installation at Riga Shipyard. Mobile accelerator unit (right) and wet scrubber (left).

The whole amount of flue gas generated by marine Diesel engine was treated in the system. After engine ignition the scrubber pump was switched on and required water flow rate was set. Water flow rate was measured by a rotameter. In the same time the accelerator was started and after stabilizing of gas flow rate the gas parameters were recorded.

Water tanks were filled up with Baltic Sea water before the series of experiments. As the salinity of the Baltic Sea is very low (0.7%), 90 kg of NaCl was added to the tanks in order to increase the salt content to mean salinity of seawater (about 3.5%). The solution was not changed during the whole cycle of experiments. In order to keep the ability of seawater for acidic gases absorption, pH of the solution was kept over 7.5 by addition of sodium hydroxide. The pH of the scrubber solution was controlled by 3210 Set 2 pH-meter manufactured by WTW (Germany). In order to enhance of the oxidation potential of the solution and improvement of NO_x removal efficiency, $NaClO_2$ as an oxidant was added to the circulating water. Total amount of 10 kg of oxidant was added leading to 3.3 g/l concentration of this agent.

The measured NO_x removal efficiencies were in good correlation with previously obtained results, however maximal NO_x removal rates didn't exceed 45% (Figure 8). Observed low NO_x removal rates may be explained by low doses applied caused by disrupted functionality of the accelerator system, mounted on the both opposite sides of process vessel. One accelerator operation resulted in the fact, that only half of possible dose was available and dose distribution was not uniform due to low penetration range electrons (electron energy was 125 keV). Part of gas stream flowing opposite to the operated accelerator window got low absorbed dose. As NO oxidation and further absorption strongly depends on the absorbed dose, such situation lead to decrease overall NO_x removal rates.

It is important to note that the pilot plant tests performed in Riga Shipyard was the first attempt to demonstrate hybrid electron beam technology in real conditions. Therefore, one of the primary objectives of this experiment was testing integration of diesel engine with accelerator and scrubber as such. This resulted very successfully and this novel technology was demonstrated, confirming that system and its arrangements are fully implementable in real field conditions. It is an significant milestone for the proliferation of the accelerator technology to the marine environment.

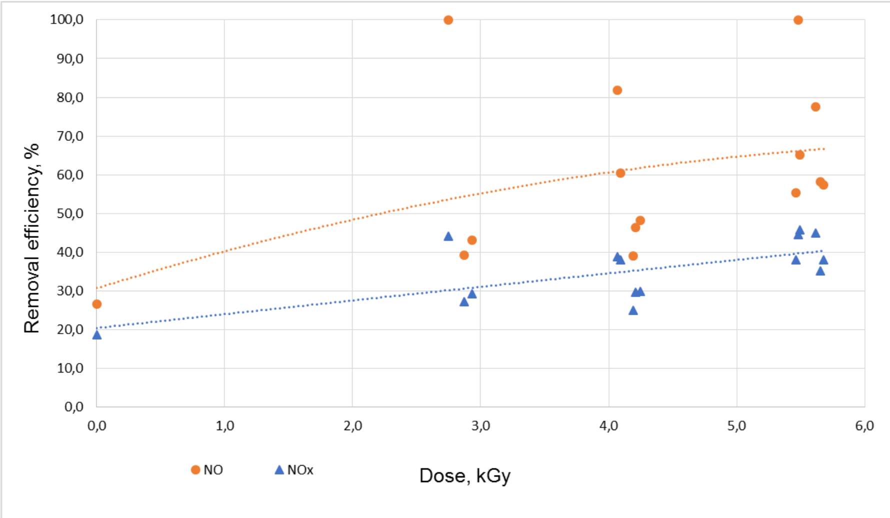

Figure 8. NO and NO_x removal rates obtained during pilot plant tests.

5. Conclusions

Both laboratory and field scale tests showed that hybrid electron beam flue gas treatment method is very promising technology to remove SO_2 and NOx from diesel engine flue gases.

Application of $NaClO_2$ as oxidation agent in the wet scrubbing solution highly increases NO_x removal efficiency in hybrid electron beam flue gas treatment process.

The highest NO_x removal efficiency (> 96%) was obtained when sea water-$NaClO_2$-NaOH was used as scrubber solution with additional injection of scrubber solution inside reaction vessel.

The operation of the pilot plant was the first case of examination of the hybrid electron beam technology in the real field conditions where it showed ability of the technology to be used in marine conditions. Taking in account the experiment conditions, good agreement was obtained with laboratory tests in the maximum available at field test dose range.

The combination of accelerator technology with wet scrubbing process is an innovative solution for simultaneous treatment of SO_x, NO_x and PM from marine diesel engine flue gases. Successful ARIES proof-of-concept tests in Riga Shipyard have demonstrated results which are opening opportunity for the further on board tests and application of the technology on board of the sea-going ships on regular routes.

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