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

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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. 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 [1]. 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 [2]. The maritime community faces a serious challenge to fulfil these limitations [3].

Existing Technologies and Prior Attempts

Cutting SO_x. To comply with sulphur emission limitations [4], the shipping industry currently has two workable options [5]: a) to opt for universal usage of expensive MGO, or b) to install exhaust gas cleaning systems (scrubbers [6]), 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 [8-12] were EU financed and presented to the stakeholders. Yet to this day, they cannot

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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 few studies have been conducted on the simultaneous removal of NO_x and SO_2 in a single process [13-16]. 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 [25-28], 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

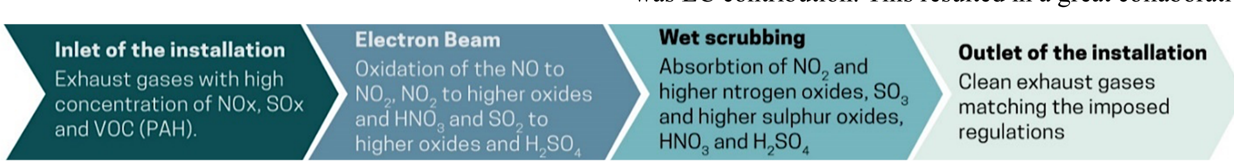

Figure 1: Principle of the hybrid electron accelerator technology for the treatment of marine diesel exhaust gases.

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spirit within this partnership, building multilateral trust and commitment to continue development of the hybrid technology until its full implementation onboard ships.

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).

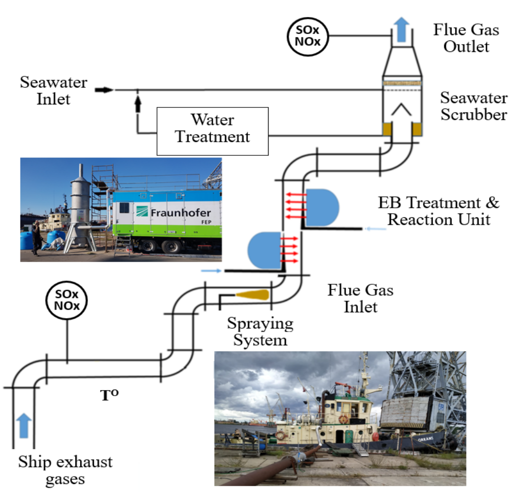

Figure 2: Hybrid electron accelerator system.

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:

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

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%], 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).

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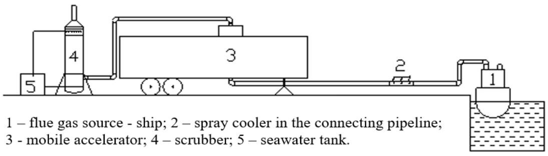

Figure 3. General scheme of pilot installation.

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 Figs. 4 and 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

Parameter	**Unit**	**Values**		
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.

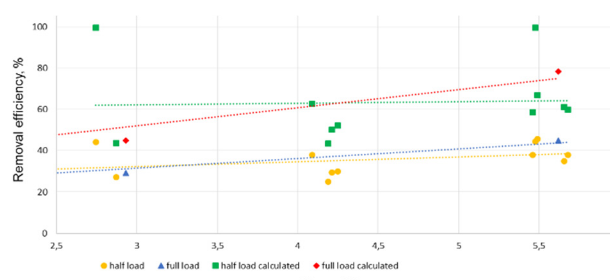

Figure 4. Dose dependence of NO_x removal efficiency for 50% and100 % engine load.

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

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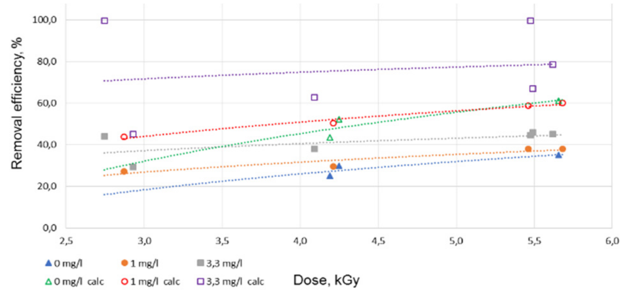

Figure 5. Dose dependence of NO_x removal efficiency for different concentrations of oxidant.

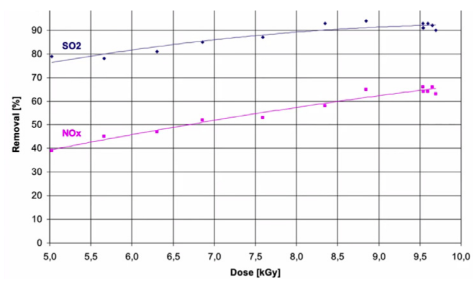

Figure 6. Dose dependence of SO_2 and NO_x matched with previous laboratory tests.

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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