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To cite this article: I Chirica *et al* 2019 *J. Phys.: Conf. Ser.* **1297** 012009

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Retrofit Solutions for Green and Efficient Inland Ships

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Abstract. The modernization of the Danube IWT fleet involves developing the needed know-how for retrofitting of the Romanian fleet in accordance with Stage V emissions legislation. The end goal is achieving lower air pollutant emissions by increasing efficiency, lowering energetic needs and decreasing the environmental footprint of the Danube IWT fleet. The following paper presents principles of the design-for-retrofitting methodology developed for inland ships. The technologies involved aim at improving the efficiency of emissions after-treatment and meeting Stage V requirements.

1. Introduction

The average age of European inland ships is about 50 years. Most of these old vessels rely on deprecated engines and diesel generators that are no longer up to date with current emissions regulation. The Danube fleet is not far from this situation. Taking into account the actual annual rate of new-build ships, the estimate is at 80 years needed to replace the current European inland fleet with new, low emission ships. Furthermore, considering that the life duration of a ship's engine is shorter than that of the ship's hull, several decades are needed to replace the inland fleet's engines with newer, cleaner and more efficient ones. As such, the retrofit solution is significantly cheaper than a new-build and is also less time-consuming, an important factor for operators.

A number of regulations regarding emissions from shipping have come into force. These impose strict levels of particulate matter and pollutants emission, which will lead to many vessels no longer being allowed to navigate because their emissions do not comply with the norms.

The new regulations, named Stage V emission limits, have been adopted by the European Parliament and the Council in July 2016 and have been published in the Official Journal of the European Union as Regulation (EU) 2016/1628 [1] in September 2016. These regulations impose restrictions on internal combustion engines installed in inland waterway vessels (considered as non-road mobile machinery). For engines (main and auxiliary) with a net power lower than 300kW, the EU Stage V emission standards have entered into force on 1st of January 2019. For engines having a net power higher than 300kW, the implementation date is set for the 1st of January 2020.

Retrofitting existing inland ships can be broken down into several points of action that need to be addressed. The most important one is reducing the environmental impact of existing inland waterborne transport. In this respect, a feasible solution is to act on the propulsion machinery by means of new technologies regarding fuel engines processes.

The cheapest way to reduce emissions is to use an after-treatment system for the propulsion engines. Current retrofit solutions are time-saving procedures when put into perspective with other alternatives.



The retrofit solution for an old ship is justifiable, especially taking into account the fact that manufacturers already have technically viable solutions and equipment is often relatively easy to replace [2].

Current activities performed by the Romanian ship design industry are undertaken in line with the policies of Connecting Europe Facility (CEF) for Transport, the main funding instrument supporting the European transport infrastructure development. The program aims at supporting investments in developing new transport infrastructure in Europe or rehabilitating and upgrading the existing one.

Design-for-Retrofit needs to also lead to the establishing of principles that show potential benefits for future maintenance and ship repair scenarios. The obtained retrofit concept requires further definition and refinement work before being applied during a vessel's design process.

Support for modernization of inland waterway freight transport is focused on three main objectives / criteria, as presented in Fig. 1: reduction of environmental impact, increasing multi-modality of freight transport and increasing safety. These criteria are based on three needs: replacing engines, investment into new ships and requirements of new prospective markets [3].

Improvement of the environmental performances of inland vessels can involve several solutions [4]:

- upgrading of internal engine (using exhaust gas recirculation - EGR, advanced injection systems, using humid air systems, in-cylinder water injection and homogeneous charge compression ignition - HCCI),

- using of more qualitative diesel fuel (e.g. low Sulphur fuel - LSF),
- using alternative fuels (biodiesel - BD, biodiesel blend - BDB, diesel-water emulsion, natural gas and hydrogen),

- using alternative combustion engines (natural gas engine),
- using new propulsion and auxiliary systems (e.g. diesel-electric propulsion & fuel cells),
- electronic drive management systems (ATM, RIS etc.),
- using exhaust gas after-treatment systems (diesel oxidation catalyst - DOC, selective catalytic reduction - SCR, particulate matter filter - PMF etc.).

Figure 1: The needs and criteria for IWT modernization

	CRITERIA		
	Reduction of environmental impact	Increasing multi-modality of freight transport	Increasing safety of IWT
	Need to replace engines	X	X
	Investment into new vessels	X	X
	Requirements of new prospective markets	X	

An important alternative to reduce toxic emissions is to use nonpetroleum diesel fuels that can be produced from renewable resources (seed oils and animal fat, synthesized from natural gas, biomass, oil sands, coal, and other resources). Cellulosic ethanol production is an important technology developed in the last decade, although the quantities produced are small. Installations for the production of renewable diesel fuel from biomass resources are not sufficiently developed. Natural gas is also a potential replacement for liquid petroleum fuels.

2. After-treatment solution for retrofitting of existing inland ships into green and efficient ships

Retrofitting is defined as the installation on-board ships of modern or innovative components or systems in order to meet new regulatory energy and emissions standards or to meet a ship owner's interest in upgrading the ship for higher operational standards.

Increased focus on global warming and environmental pollution in the last decade has led to increasingly stringent emissions monitoring in the waterborne sector.

Marine diesel engines mainly use heavy fuel oil with high Sulfur contents, resulting in gas emissions that contain a mixture of harmful chemicals (such as Sulfur oxides – Sox, Nitrogen oxides - NOx) and

particulate matters (PM). Current cleaning systems can reduce this down to harmless substances, oxygen, and water.

In order to meet Stage V emission norms, the exhaust gases produced in the engine have to undergo a cleaning process before being released into the environment. The system that cleans the exhaust gas is named Exhaust After-treatment System (EATS).

The after-treatment methods do not involve substantial changes in engine room arrangement and operations. These methods only intervene on the exhaust gases evacuated from the engine.

The most common types of after-treatment systems used in the inland shipping industry: SCR catalysts and particle filters. The SCR catalyst system is installed to reduce the emission of NO_x. The particle filters are used to reduce the emission of particulate matter (PM).

For reducing the amount of NO_x, systems like SCR catalysts, installed in engine room, use vaporized ammonia or urea, stored in special tanks. The ammonium vapors or urea are added to the exhaust gas and can reduce NO_x emissions by 70 to 90% [5, 6].

Selective Catalytic Reduction (SCR) technology is an advanced active emissions control technology system that injects a liquid-reductant agent combined with a special catalyst into the exhaust gas of the diesel engine. The reducing agent is usually urea. The mixed compound undergoes a chemical reaction that converts nitrogen oxides (NO_x) into non-toxic nitrogen (N₂), water (H₂O) and small amounts of carbon dioxide (CO₂). SCR technology has been proven to reduce NO_x by up to 90 percent.

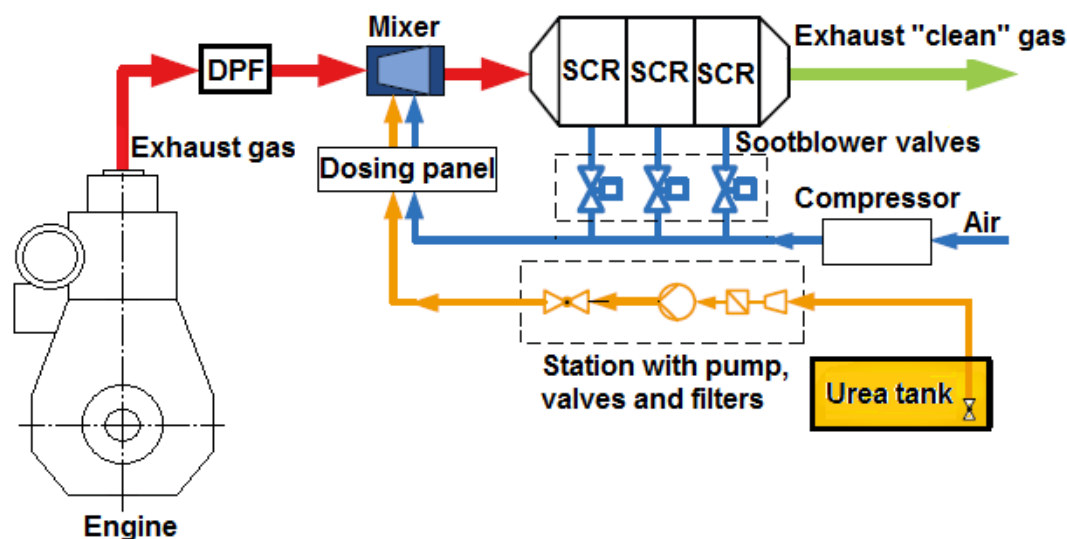


Figure 2: Principle diagram of SCR + DPF technology

Particle filters are able to reduce emissions of PM by up to 95%. As a disadvantage, the presence of filters in way of the exhaust gas flow tends to increase fuel consumption by a small margin.

Both systems are often installed together on ships with old engines (CCNR0 and CCNR1) whose operators intend on meeting the norms. The space required to install these systems in engine room is usually feasible. The investment costs are also relatively low compared to installing a new engine, up to a third lower. In addition to that, many engine manufacturers are currently not producing engines that meet the norms.

3. Technologies aimed to reduce inland vessels emissions

Compared to previous emissions legislation, where Selective Catalyst Reduction (SCR) and Ammonia Slip Catalyst (ASC) were enough as far as exhaust after-treatment systems go, the new Stage V legislation imposed the addition of a Diesel Oxidation Catalyst – (DOC) and a Diesel Particulate Filter – (DPF). Emissions from the propulsion engine have to pass through the entire after-treatment system for it to be effective and the resulting levels of pollutants to be acceptable.

3.1 PM treatment

Solutions for decreasing particulate matter (PM) emissions from a ship's diesel engines are still being developed. Treatment of particulate matter can be split into three technologies: Diesel Particulate Filter - DPF, Diesel Oxidation Catalyst - DOC and Continuous Regeneration Trap - CRT.

Diesel Particulate Filter technology involves reducing exhaust soot particles and can effectively reduce particulate emissions. This technology is based on inertial impaction, interception, diffusion and sedimentation principles. The essence of DPF technology is filter body regeneration. The actual honeycomb (made of ceramic or SiC) wall-flow particulate developed recently can filter with an efficiency of 99.8%.

To meet Stage V norms related to PM, the standardized SCR systems are combined with Diesel Particulate Active Reduction (DPR). DPR is a diesel particulate filtration system that relies on a delay of fuel injection to control exhaust gas temperature such that the soot is burned off.

In Figure 2 a principle diagram of Selective Catalytic Reduction and a Diesel Oxidation Catalyst (DOC) technology [5] is illustrated.

3.2 Principle of technologies used for inland vessels engines

Due to the using of combustion of fossil fuels in various industries, the concentration of toxic pollutants in the exhaust gas to atmosphere is very high. Toxic exhaust gases are Nitrogen oxides (NO_x), in particular nitrogen oxide - NO, nitrogen dioxide - NO₂ and nitrous oxide - N₂O, considered harmful to human health and the environment. These pollutants contribute to the greenhouse effect, participate in photochemical reactions and contribute to acid rain phenomena [6].

Nitrous oxides use nitrogen from the air (N₂) and from the fuel used (CN). These substances mainly form as a side product and not as a combustion product. Emergence of nitrous oxides is due more to the high temperatures inside the engine and only partially to the combustion flame, according to the following reaction:



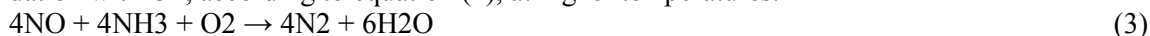
In the presence of water, NO_x react and form nitric acid or nitrous acid (leading to acid rain phenomena) according to the following reaction:



Selective catalytic reduction (SCR) is a method of converting nitrogen oxides (NO_x) with the aid of a catalyst into diatomic nitrogen (N₂) and water (H₂O).

The two principles of an SCR catalyst are thermal and catalytic decomposition of urea (CH₄N₂O) inside a reactor. SCR catalysts comprise of a carrier, usually a ceramic material, such as titanium oxide and an active catalytic component, which is either an oxide of base metals (such as vanadium, molybdenum and tungsten), zeolites, or certain precious metals. Another catalyst based on activated carbon was also developed and is usable in the removal of NO_x at low temperatures.

The reduction process of NO over a V₂O₅/TiO₂ catalyst involves two parallel reactions [7]. The main reaction is the conversion of NO to N₂, according to equation (3). The second reaction is NH₃ oxidation with O₂, according to equation (4), at higher temperatures.



The NH₃-SCR system is in principle comprised of a chamber with aqueous ammonia (solution of ammonia in water), an air supplier, heater, heat exchanger, vaporizer, mixer, injector and SCR reactor. The typical flow process is as follows [6]: aqueous ammonia is pumped into the vaporizer before being mixed with hot air. Then, gaseous ammonia as a reducing agent (reductant) is injected into flue gas that is preheated in the heat exchanger. The gas mixture then flows into the SCR reactor. Discharged clean gas flows into the heat exchanger to heat the input flue gas. In the SCR process, a gaseous reductant is typically pure anhydrous ammonia, aqueous ammonia or urea. The chemical reactions that occur in NH₃-SCR systems are shown in equations (3) and (4) where the first one is the desired reaction. Precise control of ammonia injection rate is needed in order to obtain desired NO_x conversions and to avoid

release of undesirable ammonia to the atmosphere. Ammonia emissions from SCR systems are known as ammonia slip.

Performance tests of SCR developed nowadays demonstrated that the system's performance is significantly improved in modern equipment. The NH₃ conversion rate can be increased significantly with advanced mixing elements [7].

DOC technology aims to oxidize the pollutants in exhaust gases. During the passing of exhaust gases through the catalyst, hydrocarbons and carbon monoxide react with oxygen (O₂) resulting in H₂O and CO₂. This technology is available for diesel fuels with low sulfur contents. Existing sulfur in the fuel oxidizes into SO₂ and SO₃, which then react with water and are converted into sulfates. DOC technology eliminates PM by oxidizing the soluble substances. Current DOC implementations can reduce CO emissions by up to 30% and HC emissions by up to 50%.

4. Design-for-retrofitting methodology

4.1 Principle of Design for retrofitting

Retrofitting ships with green technologies aims at improving their environmental performance by lowering energy usage and emission levels, without altering the ship's operational profile. Implemented changes are restricted by existing hull geometry and machinery arrangements.

Before starting the retrofitting design, certain steps need to be performed.

- Confirming that the selected ship is suitable for retrofitting (life cycle, operational facts etc.);
- Assessing the ship's performance on energy usage, emissions and safety;
- Identifying appropriate green technologies and the corresponding hardware, equipment, systems etc.;
- Analyzing the feasibility of merging the proposed solution into existing arrangements (space, machinery, equipment, piping, cabling, fittings etc.) while keeping the costs as low as possible;
- Determining the impact of the retrofitting technology on the vessel's performances;
- Establishing the possibility of monitoring the ship's performances;

For the moment, a solution used as a transition method to decrease the emissions according to Stage V is to use additional systems to treat the exhaust gas in order to meet the requirements. Therefore, improving emissions control systems is used as a complementary tool to sustain the engine combustion processes.

Including the after-treatment systems on board depends on the available space. For particular vessels, the available space can be limited. Inland ships tend to have small engine rooms. In these cases, adequate retrofitting solutions have to be adopted. In certain cases, connecting points to the ship's structure are necessary. The equipment involved might have a significant weight and could generate additional vibrations and dynamic forces that can be diverted towards the ship's steel structure.

The design for retrofitting works related to after-treatment systems are [8]:

- Removal of existing exhaust system and replacement of the silencers with the new after-treatment modules.
- Installation of the new after-treatment modules.
- Rerouting of the existing pipe network in the casing.
- Installation of new pumps.
- Installation of the new exhaust system piping.
- If necessary, modifying the funnel casing.
- Installation of new cabling, control systems and insulation.
- Structural modifications and other auxiliary jobs.

4.2 Design for retrofitting of an inland vessel

The SCR+DPF technology was selected for retrofitting of an inland pusher belonging to the Romanian Danube fleet. The vessel is equipped with two identical propulsion lines, each one consisting of: one fixed pitch ducted propeller, shaft line, reversing reduction gearbox and main engines with a classic

exhaust system. The propulsion arrangement and the existing main engine exhaust system are presented in the Fig. 3.

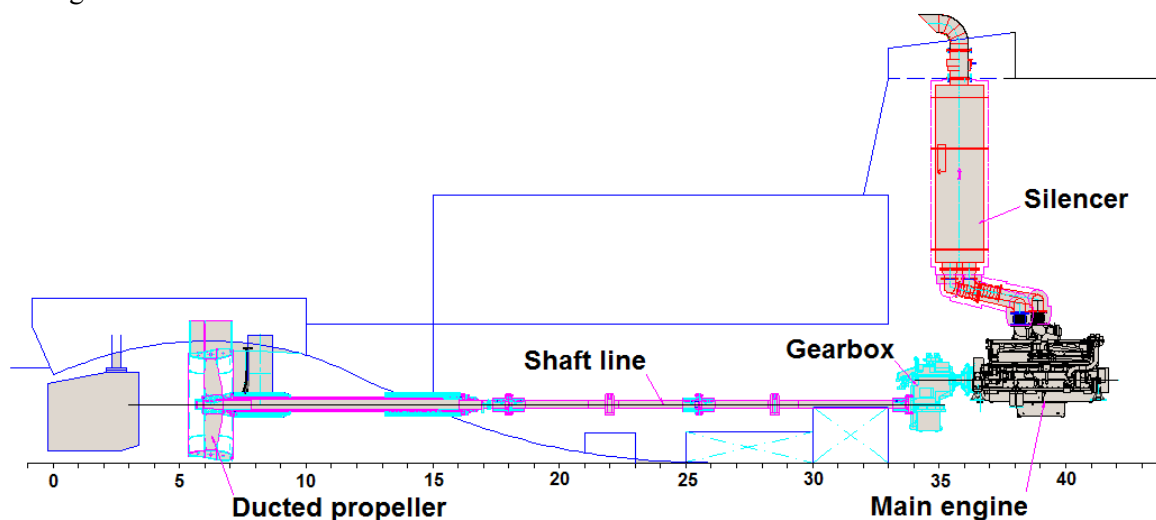


Figure 3: Existing propulsion system on inland ship

According CCNR Stage V Regulations the new emission limits apply to both propulsion and auxiliary engines that produce an output power equal to or greater than 19kW. The result is that the vessel operator has to eventually replace all existing internal combustion engines on board with Stage V compliant engines. Piping systems modifications were performed for exhaust, cooling, fuel, lubricating, compressed air and ventilation systems.

Structural modifications were performed for engine foundations, exhaust system (supports and funnel), and a urea tank was added.

The new engine is delivered together with an exhaust after-treatment system (EATS) in order to meet the pollution requirements imposed by CCNR Stage V (DPF+SCR).

Since existing equipment was removed (as is the case of the exhaust silencer), no supplementary space was needed for the new equipment.

5. Conclusions

Regarding state-of-the-art in solving the design for retrofit activity, it is useful to consider that retrofit is a continuous process to improve its economics at an existing or new system.

In the paper, certain systematic procedures starting to emerge, especially for exhaust gas treating network, to a lesser extent for improving economics, energy efficiency and flexibility in continuous propulsion processes is described.

The retrofitting systems can be implemented successfully in shipbuilding in order to decrease the emissions. In most cases, the engine does not need to be modified or repositioned. Retrofit systems are cheaper than overhauling the ship.

One disadvantage of retrofitted systems is that the components in them are quite small. Maintenance is difficult and requires some expertise. Parts are also difficult to manufacture and replacing them involves assistance from the manufacturer of the equipment.

Another disadvantage of retrofit systems is that merging them into an already highly complex system is usually no longer practical cost and time-wise. In such situations, it is perhaps more suitable to replace the existing engines with ones that comply with Stage V regulations.

SCR is one of the most cost-effective and efficient retrofit technologies aimed at reducing a ship's engine emissions.

In principle, retrofitting involves different design approaches for each vessel and situation.

Acknowledgement

The paper has been supported also by Doctoral School of Mechanical and Industrial Engineering from University Dunarea de Jos of Galati, Romania.

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