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ANALYSIS CONCERNING POSSIBILITIES OF ADJUSTABILITY OF CRUISE FERRIES AND RO-RO VESSELS OPERATING ON THE BALTIC SEA TO THE REQUIREMENTS OF ANNEX VI OF THE MARPOL CONVENTION

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Abstract

The goal of the paper is to focus on the problem of emission of harmful compounds e.g. NOx, SOx and CO_2 from seagoing ships to environment. The VI Amendment to MARPOL Convention concerning prevention against air pollution by seagoing ships, brought into practice in May 19th 2005, forced ship owners to use means for reduction of environment harmful substances emission to atmosphere. They may comprise construction and operating methods. Energy Efficiency Design Index (EEDI) is one of the tools enabling implementation of the above-mentioned regulations, compulsory to all new design and build ships. However, for units already in operation, the problem requires a different approach. The article presents various methods of reduction of toxic substances and CO2 by seagoing vessels in order to adapt to the requirements of the Convention and other legal regulations in this regard. As an example, the analysis has been presented concerning possibilities of adjustability of cruise ferries and Ro-Ro vessels operating on the Baltic Sea to the requirements of Annex VI of the MARPOL Convention. Some possible solutions have been shown focusing on selection of system of combustion of hydro-fuel emulsion in main drive engine. Article contains description of introducing water to the combustion chamber methods and water influence on the combustion process.

Keywords: *cruise ferry, ro-ro vessel, toxic compounds, carbon dioxide, air pollution, environmental protection, fuel-water emulsion*

1. Introduction

The effects of the fuel combustion in marine engine are exhaust gases. These gases consist of toxic compounds like:

- Nitrogen oxides (NOx) – most toxic. NOx that react with steam in the air and create nitric acid, causing acid rain. Also they are responsible for decay of the ozone layer, the greenhouse effect and they can cause cancer,
- Sulphur oxides (SOx) received in oxidation of marine fuel containing sulphur, where fuel can consist even of 3.5% of sulphur, SOx react with steam in the air creating acid rain, that is harmful to people, animals, plants and other objects,
- Carbon oxides (CO) are the products of non-total oxidation of marine fuel. The combustion reaction does not have enough oxygen to create CO_2. Carbon oxides are toxic gases, causing lethal poisoning,
- Hydrocarbons (HC) received in the process of non-total and incomplete fuel and oil oxidation comprise many chemical particles and compounds like methane. They are harmful to human health as well as to the environment. They can cause the greenhouse effect,
- Particulate Matter PM can be of solids or liquids consistency. They can be particles of non-combusted fuel like soot, heavy hydrocarbons or compounds of nitrate and sulphur.

Moreover, exhaust gases consist of carbon dioxide (CO_2). They are received during total oxidation of non-toxic but causing greenhouse effect hydrocarbons.

Revised VI Amendment to MARPOL Convention introduced in May 19th 2005 concerning protection against air pollution by seagoing ships forced ship owners to apply solutions allowing reduction of air harmful substances to atmosphere. International Maritime Organisation IMO determined ECA (Emissions Control Areas) where emission of nitric oxides NO_x is restricted. The limit of NO_x emission (Tab. 1) was determined by IMO in MARPOL Convention and named Tier III to be in force from January 1st 2016.

Tab. 1. Permissible NO_x contents in exhaust gases according to VI Annex to MARPOL Convention

Year	**Permissible contents of NO_x [g/kWh] in exhaust gases at different rotational speed of engine n [rpm]**		
	n < 130	**130 ≤ n < 2000**	**n ≥ 2000**
2000 (Tier I)	17.0	$45 \cdot n^{-0.2}$	9.8
2011(Tier II)	14.4	$44 \cdot n^{-0.23}$	7.7
2016(Tier III)*	3.4	$9 \cdot n^{-0.2}$	1.96

**Maximum No_x contents on ECA areas. On areas outside ECA the contents limit from the year 2011 is valid.*

However, these requirements valid from January 1st 2016 were conditional. They can be valid if the technology of NO_x emission reduction to such low level is available. Analysis carried out by IMO pointed out that it is not possible in supposed date. The date of Tier III being in force was postponed probably to January 1st 2021. The date of changes will be announced on the nearest session of IMO MEPC (Marine Environment Protection Committee). It means that for the time being standards of Tier II concerning NO_x emission are in force.

The permissible level of sulphur dioxide SO_x emission from ships was determined by specifying the permissible contents of sulphur in marine fuel on SECA (Sulphur Emission Control Area) areas. The limit of 0.1% sulphur contents in fuel will be in force on SECA areas from January 1st 2015.

In European Union harbours regulations concerning restrictions of sulphur dioxides emission are valid earlier i.e. from January 1st 2010. They request maximum 0.1% sulphur contents in the fuel of seagoing ships and inland vessels during berthing in port. Low sulphur fuels are not requested during manoeuvring but should be used as soon as possible after port calling and as late as possible after port leaving.

The first text of VI Amendment to MARPOL Convention concerning preventing air pollution from seagoing ships did not include restrictions of carbon dioxide emission. However, greenhouse effect hazard was noticed by IMO and other international organisations. At July 2011 the VI Amendment was revised by fourth chapter concerning limitation of greenhouse gases emission from seagoing ships especially carbon dioxide emission. Regulations valid from January 2013 request from owners to introduce plan of effective energy management during ship operation SEEMP (Ship Energy Efficiency Management Plan).

To minimize CO_2 emission from January 1st 2013 all new built ships above 400 BRT should have determined Energy Efficiency Design Index (EEDI). EEDI should be used for control of CO_2 emission from ships. EEDI [g/t*NM] is defined as a ratio of emitted CO_2 [g] to the weight of cargo [t] carried on 1 Nautical Mile [NM] distance of specified trade line.

The value of EEDI calculated according to prescribed procedure should be equal or lower than value determined for given type and size of ship.

All these law regulations enforce ship owners to apply solutions that reduce the emission of toxic gases and carbon dioxides into the atmosphere. These solutions can be introduced during designing the ship or building the vessel or even later during exploitation of the ship. The most popular ways are:

1. Reduction of exhaust gases in toxic substances, by modification process of combustion and exhaust gas treatment system.

2. Reduction of fuel consumption by applying new ergonomic hull shape economic engine and efficient propeller.
3. Using low sulphur fuel and methanol.
4. Supply engine with gas fuels.

Usage of new construction of the hull, propeller and engine can be arranged during designing and building a new vessel. Using low sulphur fuel is more expensive and has negative impact on engine work. Methanol is a toxic substance to human health. During engine combustion methanol cannot reach the auto-ignition point, which is why it is required to implement modifications in the engine like mounting spark plug or adding additional dose of pilot diesel oil fuel. Using gas fuels requires modifications of fuel line installation. Such a project is very expensive. Therefore the best way to reduce toxic substances received in the process of combustion is modification of the combustion process and exhaust gas treatment system for passenger ro-ro sea vessels on the Baltic Sea.

2. Methods of reducing toxic substances included in exhaust gases done by forming combustion process and treatment system

The reduction of emission of toxic gases (NOx) in marine engine exhausted gases can be achieved in two ways: the primary method, the secondary method or by applying both methods simultaneously.

Primary method

The primary method prevents receiving toxic substances during the process of combustion in the engine chamber done by optimizing of this process and ensures proper chemical composition in engine combustion chamber [8]. Temperature of cylinder gases and partial pressure of oxygen and nitrogen have the most significant effect on the amount of received nitrogen oxides. The primary method focuses on:

- decrease of the maximum temperature of exhaust gases done by: direct water injection to the cylinder, supplying engine with water and fuel emulsion or scavenging air humidification,
- decrease temperature and pressure in initial time of combusting done by injection delay or gradual injection,
- applying special injector nozzle that optimizes combustion process and minimize the amount of NOx,
- exhaust gas recirculation – reintroducing small amount of exhaust gases with non-combusted fuel to scavenging air it reduces the quantity of oxygen and in consequence decreasing the temperature of combustion and NOx emission,
- compression ratio change,
- reduce scavenging air pressure.

This method allows achieving Tier II requirements, but may not allow achieving Tier III standard.

Secondary method

Secondary method focuses on eliminating nitrogen oxides by exhaust treatment system outside the engine. This method does not require engine construction modification and do not changes combustion process. Several chemical reactions like absorption, adsorption and catalytic reduction can be used to reduce the quantity of NOx in exhaust gases. SRC= Selective Catalytic Reduction is recognized as the most efficient method of reducing the amount of particulate matter and nitrogen oxides in the exhaust gases. This method converts toxic nitrogen oxides into atmospheric nitrogen and steam. Ammonia and urea is used as redactor in a catalyst converter. This method reduces NOx by 90%; it also decreases the quantity of carbohydrates and soot. Maintaining the temperature 300-400°C is very crucial in this process. Higher temperature can cause urea decay but lower temperature radically slows down the efficiency of the reaction. This solution is preferred for a 4-stroke engine because of its more stable combustion process and higher exhausts gases temperatures. However, 2 stroke engines have more unstable working process and the temperature of exhaust gases is often below 300°C.

What is more the secondary method can be realized by using scrubber system. Scrubber reduces only SOx. It uses adsorption and absorption processes often combined with chemical reaction. A few methods can be distinguished depending on the product treatment:

- waste method – whose products after the reduction of SO2 with the usage of absorbent or adsorbent are stored or deposited in sea,
- semi waste method – whose products can be stored or deposited in the sea, the products of the reaction are not dangerous to the environment,
- non-waste method – whose sorbents are regenerated and reused. Received SO_2 is converted into useful products like sulphur acid or reduced to pure sulphur.

Described above scrubber methods are divided into: wet method (absorption reaction), dry method (adsorption reaction) and semidry method. The most popular method on the land is the wet method. On the vessel, the most popular is waste method using seawater as a substratum of the reaction. These processes take place in scrubber, which is placed instead of exhaust silencer. In the scrubber heat and mass exchange, take place between exhaust gases and countercurrent sprayed water.

Combined method

The best results can be achieved by using simultaneously both methods: primary and secondary. Its example can be the engine that uses water and fuel emulsion and afterwards, exhausted gases are reduced by Selective Catalytic Reduction. Therefore nitrogen oxides can be reduced by up to 90%

3. Application of water and fuel emulsion to modifying combustion process in marine engine

The process of reducing toxic substances in exhausted gases done by Selective Catalytic Reduction and using scrubber is require installing big and heavy installations on the vessel. Often it is needed to build an additional funnel that worsens the vessel stability and limits the cargo space. The most rational way to reduce toxic gases of ro-ro ferries cursing the Baltic Sea (regulated by emission control area) is modification of combustion process. It can be achieved by decreasing maximum temperature of combustion, using direct water injection to the cylinder or by combusting water and fuel emulsion. Described methods reduce nitrogen oxides. Sulphur oxides reduction is achieved by supplying the engine with low sulphur fuel.

Ro-ro ferry STENA SPIRIT installed LEMAG water in fuel system (WIF). This system supplies main engines with water and fuel emulsion. The scheme of WIF system is presented on a Fig. 1.

The essence of WIF system is creating water and fuel emulsion, which is combusted in marine engine. Due to water, the maximum temperature is decreased and the quantity of NOx is much lower.

In nature, water and oil cannot create emulsion. The emulsion can be received by emulsification or homogenization. Emulsification requires adding solution emulsifier to make emulsion permanent and then mechanically mix water and oil. Such method does not take place on vessels. Better way to make emulsion is homogenization. Oil and water are mixed mechanically. The disadvantage of such a method is the fact that emulsion is not permanent and cannot be stored in tank. It must be produced constantly and immediately combusted in engine.

LEMAG's WIF system (Fig. 1) water and fuel is premixed in Water Injection Nozzle. To mix heavy fuel oil it is needed to preheat water in Water Heater. Heating media is steam its pressure is 0.6 MPa. Preliminary mixed water and fuel go to LEMAG Safety Homogenizer. Homogenizer's basic compounds are rotor and stator. Due to special grinding, there is a narrow gap between them. Rotor rotates at high speed; in effect, there are big friction forces between water and oil causing emulsion. Module construction of the homogenizer presents Fig. 2. Later the emulsion goes to Booster Pomp and then through to the Final Heater to the engine. The excess of the emulsion goes through static Pressure Regulating Valve to the Buffer Tank, which is connected with Degassing Tank.

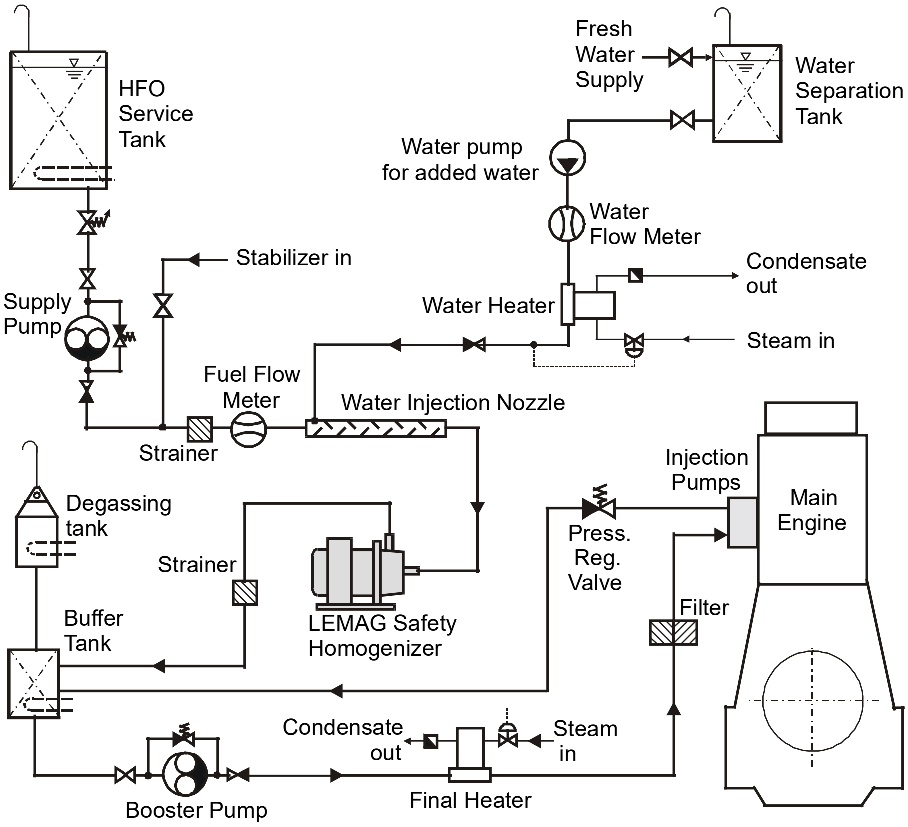

Fig. 1. The scheme of the WIF system

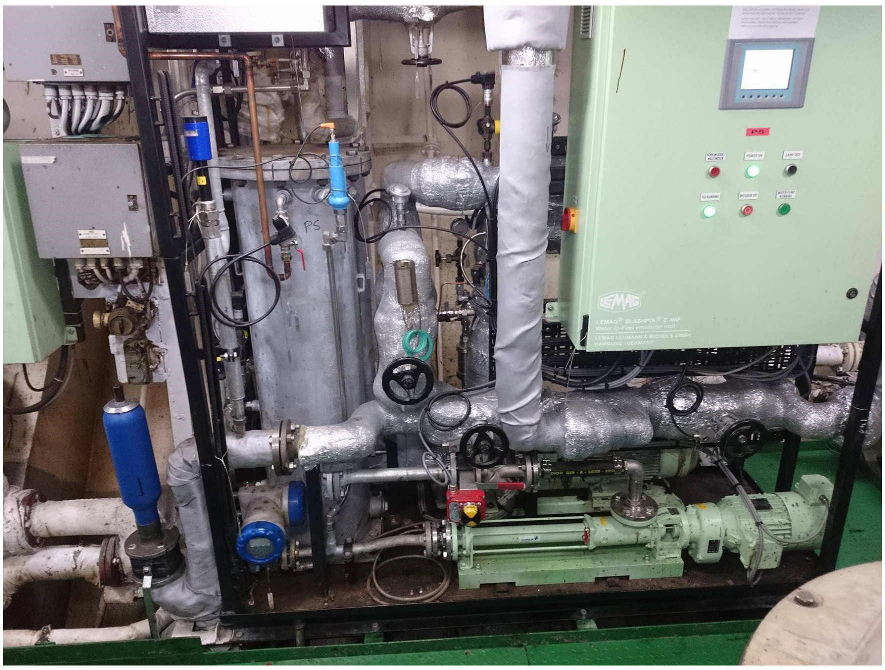

Fig. 2. The view of the WIF system

After installing the WIF system on STENA SPIRIT ferry its exploitation began. Initially the content of water in the water – fuel emulsion directed to the main engine was 18%. Such a proportion caused decrease in generated power as well as water collected in filters. Later inspection proved that there was rust and white dirt on a cylinder and piston. Because of it the water content gradually decreased at first up to 12% and then up to 8%. During combustion of 8% emulsion, no power loss was observed.

The authors of this article carried out a research on STENA SPIRIT ferry using the exhaust gases analyser MRU GA 9000 supported with MRU 96/2 D computer. The measurements were carried out for 3 exploitation situations:

- during starting the main engine and manoeuvres, when the main engine was supplied with heavy fuel oil RMD 80,
- during voyage, when the main engine was supplied with fuel – oil emulsion: the content of water rose gradually from 2% to 18%,
- during the entering to the harbour manoeuvres, during that time the fuel was changed from 18% emulsion to the heavy fuel oil.

Figure 3 presents a diagram showing received measurements. It presents the variation of generated power and specific fuel consumption depending on the fuel used.

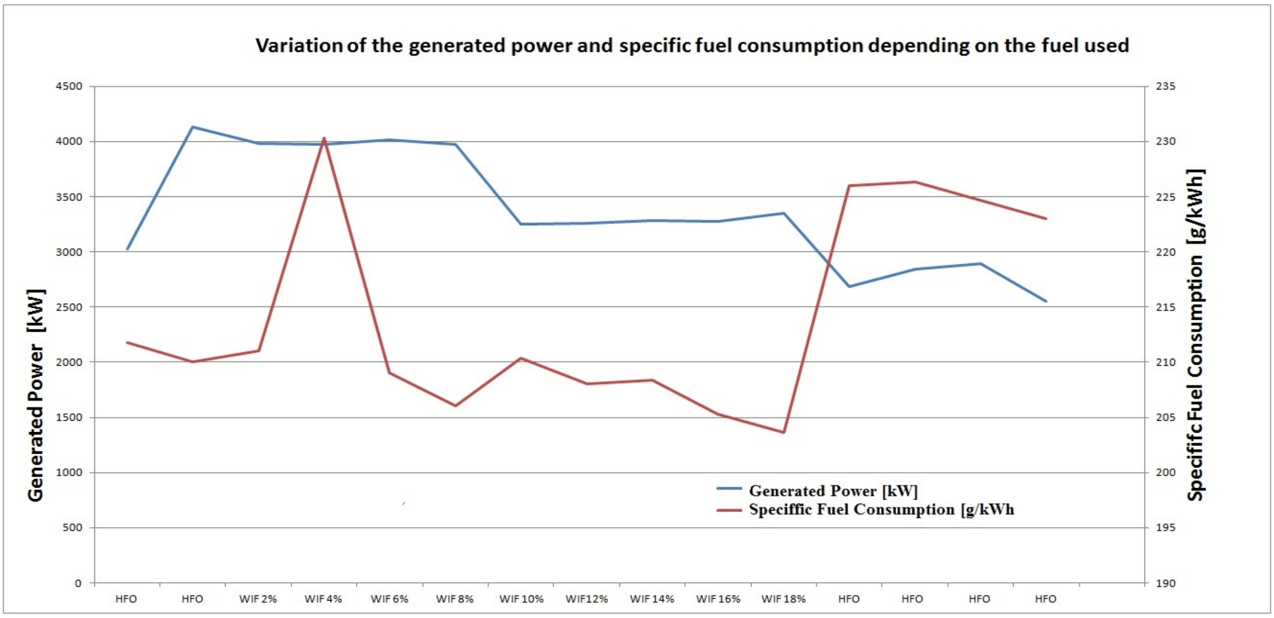

Fig. 3. Variation of the generated power and specific fuel consumption depending on the fuel used

The analysis of drawing 3 shows that the most economical way of supplying main engine is combusting 8% emulsion.

In this case, the generated power stays on the high level what is similar to the situation when the engine was run on pure heavy fuel. The specific fuel consumption decreases significantly.

The Fig. 4 shows quantity of NOx contained in exhausted gases, depending on combusted fuel**.**

In the drawing the referenced lines show maximum quantity of NOx that refers to the main engine Sulzer 16 ZV 40 working at rotation speed 430 rpm. These lines show the requirements of the MARPOL annex VI for TIER I II and III. The blue line shows that combusting fuel – water emulsion can decrease the quantity of NOx only below the level of TIER II. It could not be achieved by combusting pure heavy fuel oil. Meeting the restrict requirements of TIER III cannot be achieved using WIF system.

The quantity of SOx and soot in exhausted gases was measured during the research. Exhausted gases analyser proved that there are no SOx, what is caused of combusting low sulphur fuel. In such fuel, the content of sulphur should remain below 0.1% of total mass. The amount of soot remained on the same level. Even increasing the amount of water in emulsion did not cause decreasing soot quantity.

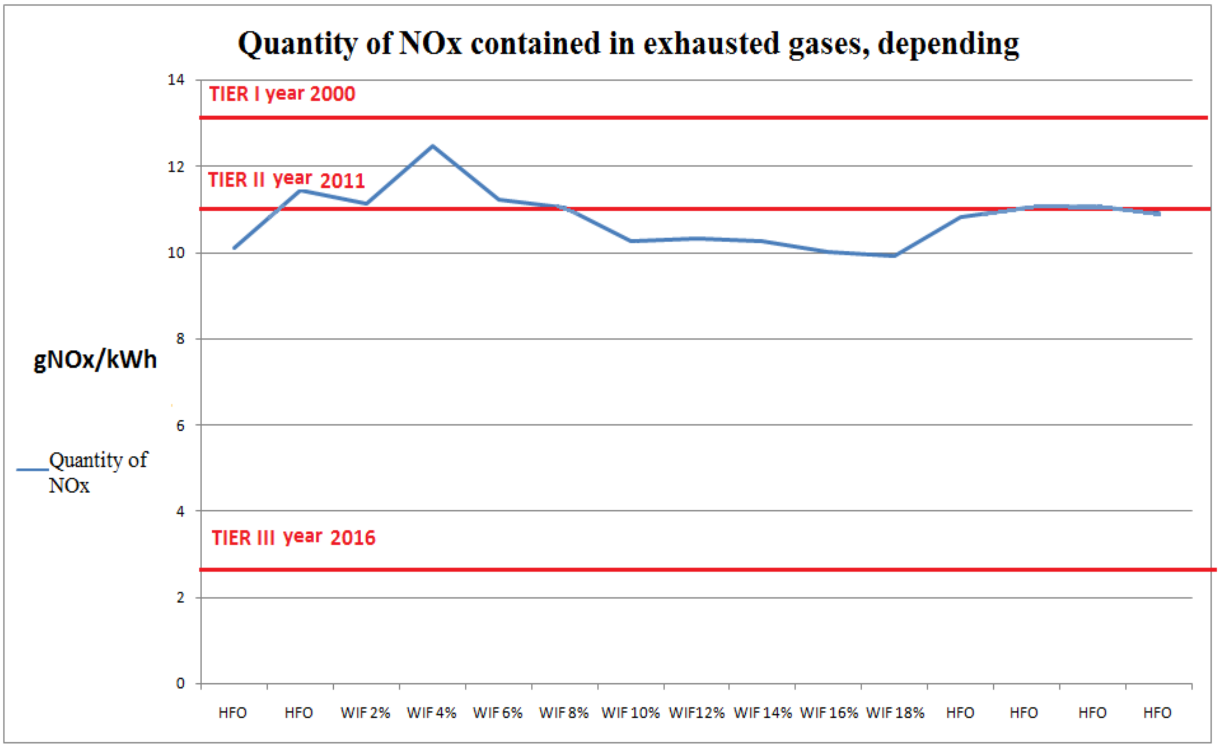

Fig. 4. Quantity of NOx contained in exhausted gases, depending on fuel used

4. Conclusions

Annex VI MARPOL convention concerning prevention of air pollution, introduced in May 19th 2005, forced ship owners to use solutions that decrease toxic gasses emission like SOx, NOx and other gases into the atmosphere. The Baltic Sea is a very restricted area; in addition, vessels on this area have to fulfil the ECA and SECA requirements.

Reduction of toxic gases emitted to the atmosphere can be obtained in new built vessels by applying new constructions of engine room, like combusting LNG fuel in new dual fuel main engines.

As to the vessels already in exploitation, a new approach to the issue is required because there is a need for modification of engines in exploitation to fulfil the requirements of MARPOL regulations what can be achieved by decreasing the maximum temperature of combustion by direct water injection to the combustion chamber or by combusting water and fuel emulsion. These methods reduce emission of NOx. An alternative, not demanding modification in the engine, can be combusting methanol. Reduction of SOx emitted can be achieved by combusting low sulphur fuel.

Stena Line Company's ships combust low sulphur fuel. STENA SPIRIT ships owners installed WIF system that combust fuel and oil emulsion. On STENA SCANDINAVICA main engine is supplied with methanol. After a few months of exploitation, engineers of both ferries stated that WIF system is more economical and efficient method. It is more reliable than the methanol combustion system that causes cumbersome problems e.g. leakages. TIER III standards refer to new built vessels; they are not required to old vessels already being exploited. These both systems were installed not because of constraint but because of STENA LINE pro-ecological politic. This article should be a clue for engineer designers stating that WIF system is not efficient enough to gain TIER III level.ds.

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