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ANALYSIS CONCERNING POSSIBILITIES OF REDUCTION OF TOXIC SUBSTANCES AND CO_2 EMISSION BY USE OF DUAL FUEL DIESEL ENGINES FOR SEAGOING SHIPS MAIN PROPULSION

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Abstract

The goal of the paper is to focus the problem of emission of toxic compounds e.g. NO_x, SO_x 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. Considerable reduction of these harmful substances can be use dual fuel diesel engines for ship propulsion. Dual fuel engines are fuelled by natural gas having methane as main component. Leading producers of marine diesel engines introduced into production diesel engines DF (Dual Fuel) type. These engines can be fuelled alternatively with natural gas or with heavy fuel oil and marine diesel oil. Today the propulsion by diesel engines fuelled with natural gas is the most popular on ships carrying natural gas cargo i.e. LNG carriers (Liquefied Natural Gas Carriers). Natural gas is freight in liquid form under atmospheric pressure in temperature -163 °C. Due to heat penetration into cargo tanks, the liquefied gas evaporates. Evaporated cargo BOF (Boil Off Gas) is used as a fuel in ship diesel engines. However, dual fuel engines are used on other types of ships not only on LNG carriers. A number of seagoing ships fuelled with natural gas are now under construction. For example container ship 9,000 TEU in Japan shipyard Kawasaki Heavy Industries or container ship 14,000 TEU in Korean shipyard Daewoo Shipbuilding & Marine Engineering for company CMA-CGM. Ships fuelled with natural gas e.g. modern ferries are also built by Stocznia Remontowa Shipbuilding in Poland for Norwegian owner. Adaptation of presently operated ships for fuelling with natural gas is also considered.

***Keywords**: toxic substances, carbon dioxide, fuel consumption, dual fuel engines, natural gas*

1. Introduction

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]		
	$n < 130$	$130 \le n < 2000$	$n \ge 2000$
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 the 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. The index extorts changes in ship construction and operation, which should result in reduction CO_2 emission by means of:

- reduction of ship speed,
- raise of energetic efficiency due to utilization of ship energetic plant waste heat,
- reduction of ship main propulsion power,
- use of ecological fuel e.g. LPG and LNG for ship engines fuelling,
- optimising of hull shape,
- optimising of propellers and propulsors shape,
- use of paints minimising hull resistance etc.

Among construction factors included in EEDI, a considerable benefit can give the use of ecological gas fuels LPG or LNG. It allows achieving required value of EEDI. In addition, the use of gas fuels makes possible to fulfil very restrictive Tier II standards concerning reduction of NO_x and SO_x emission from ships as well as Tier III standards in the nearest future.

Actually valid Tier II standard allows contents 14.4 g/kWh of nitric oxides in low speed diesel engines exhaust gases. According to Tier III standard this contents will be reduced to 3.4 g/kWh. In addition, the request to reduce the sulphur in marine fuel on Baltic Sea and North Sea creates the dilemma for owners: to use diesel engines with additional processing of exhaust gases or use dual-fuel engines fuelled with gas fuel. Fuelling with gas fuel LNG makes possible considerable reduction of harmful substances emission to atmosphere.

If the amount of atmosphere harmful substances emitted from diesel engine fuelled with heavy fuel oil is assumed as 100%, than for the same power engine fuelled with natural gas the emission of harmful substances is reduced accordingly: for carbon dioxide 25% less, for nitric oxides 85% less, for sulphur oxides 100% less and for solid particles 100% less. 25% less carbon dioxide emission comes from higher calorific value of natural gas (about 50 MJ/kg) than heavy fuel oil (about 40 MJ/kg). It is shown in Fig. 1 according to [3].

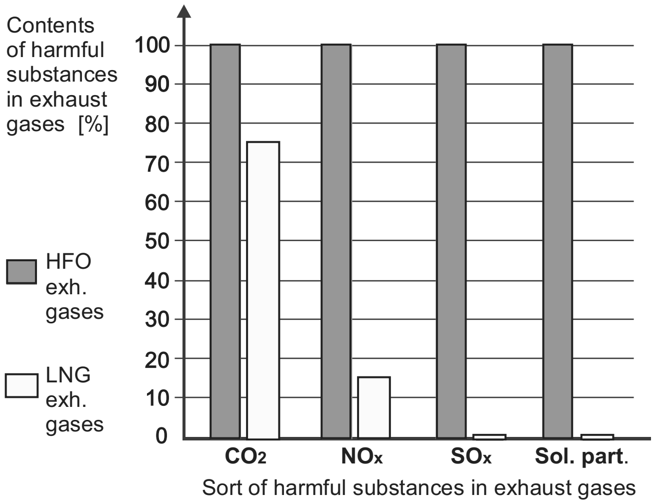

Fig. 1. Comparison of harmful substances contents in exhaust gases of diesel engines fuelled with heavy fuel oil and natural gas [3]

The conclusion is that natural gas fulfils requirements of revised VI Amendment to MARPOL Convention as marine fuel in view of atmosphere harmful substances emission after combustion. Thus, the natural gas is alternative fuel for heavy fuel oil.

2. Use of Dual-Fuel diesel engines for seagoing ships propulsion

Fuelling diesel engines with natural gas is especially useful on ships carrying natural gas cargo i.e. Liquefied Natural Gas Carriers (LNG carriers). Natural gas shipment is carried under atmospheric pressure in temperature –163 °C. Heat penetration, into cargo tanks results in liquefied gas evaporation. Evaporated gas named Boil off Gas (BOF) can be used for ship propulsion or condensed in special system and returned in liquefied form into cargo tanks.

Necessary reduction of atmosphere harmful substances emission and establishment of toxic substances emission control areas effects in projects of dual-fuel main propulsion engines use on other types of ships. Number of ships operating in offshore oil industry is equipped with dual-fuel engines working in diesel-electric systems. It comes from availability of natural gas from crude oil bed.

In Poland Remontowa Shipbuilding constructs ships fuelled with natural gas, for example modern ferries for Norwegian owner.

Natural gas system fuelling of low speed diesel engine is more complicated than the same of medium speed diesel engine is. The gas fuel for low speed diesel engine should be delivered under higher pressure so that high-energy consuming multistage compressor systems are to be used. Complicated technical system by nature is susceptible for average. That is why low speed diesel engines gas fuelling is still in project and experiment phase. However, prognosis of problem show that low speed engines gas fuelling will be introduced in the nearest future. Nearly simultaneously two Classification Societies (DNV and BV) accepted two independent projects of large container vessels driven by low speed, dual-fuel diesel engines. Norwegian DNV will supervise construction of 9,000 TEU container ship in Japan shipyard Kawasaki Heavy Industries, while French Bureau Veritas will classify 14,000 TEU container ship built in Korean Daewoo Shipbuilding & Marine Engineering for company CMA-CGM. Main engines of these ships will be fuelled with natural gas on ECA areas and with marine heavy oil on areas outside ECA. To minimise evaporation of natural gas storage tanks will be specially insulated. Both projects predict use of rectangular Type B, low pressure, LNG storage tanks, which had better utilise the space of hull than actually used cylindrical tanks. The way of foundation and location of LNG storage tanks on 9,000 TEU container vessel is shown in Fig. 2. They are located under bridge and accommodation superstructure in "double island" ship hull construction. This way the additional space for containers is obtained.

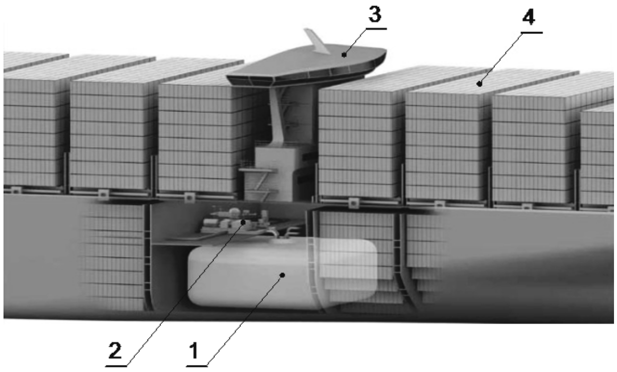

Fig. 2. Location of rectangular Type B LNG storage tank LNG storage tank on midship below bridge according to: DNV/KHI [2], 1 – LNG storage tank; 2 – gas supply module; 3 – bridge (wheel house); 4 – containers

Both new built container ships will be driven by two stroke low speed dual-fuel diesel engines electronically controlled, equipped with exhaust gas recirculation system (EGR) to minimize nitric oxides emission according to Trier III standard. Application of EGR system results in:
- acceleration of fuel evaporation during combustion process due to warming up,
- lowering temperature of combustion due to lean fuel-air mixture,
- oxidation of not burned hydrocarbons contained in exhaust gases.

In addition, optimization of new ships hull shape should ensure minimization of fuel consumption this way minimizing environment harmful substances emission.

3. Systems of diesel engines fuelling with LNG

Leading producers of marine engines introduced to offer dual-fuel engines (DF engines), which can be fuelled with natural gas and alternatively with heavy fuel oil or diesel oil.

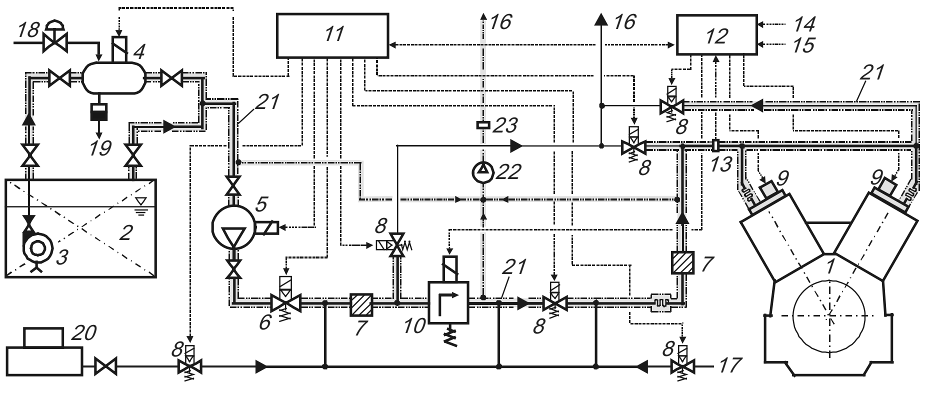

Fig. 3. Medium speed diesel engine gas fuelling system [1], 1 – medium speed diesel engine; 2 – LNG cargo tank; 3 – liquefied gas pump; 4 – vaporiser; 5 – compressor; 6 – gas main cut off valve; 7 – filter; 8 – electro-pneumatic valve; 9 – gas nozzles unit on engine cylinder head; 10 – gas pressure on engine inlet controller; 11 – system control panel; 12 – engine control panel; 13 – pressure sensor; 14 – engine revolutions signal; 15 – engine load signal; 16 – vent; 17 – compressed air inlet; 18 – heating steam inlet; 19 – condensate outlet; 20 – nitrogen generator; 21 – safety pipe of gas piping; 22 – exhaust fan from safety space; 23 – gas sensor

Medium speed diesel engine LNG fuelling system on LNG carrier is shown in Fig. 3. Evaporated in cargo tanks 2 gas is drawn in by compressor 5 and under pressure 0.8-1.0 MPa and via control unit 10 is supplied to nozzles 9 located before inlet valves on engine cylinder heads. In case of insufficient evaporation of gas in cargo tanks, a liquefied gas pump 3 and vaporiser 4 can be used. The whole system is automatically controlled by control panel 11 cooperating with engine control panel 12. The ignition of gas is executed by pilot dose of liquid fuel controlled by engine control panel. Any time the fuelling of engine can be changed over from LNG to liquid fuel end vice versa without load change. Simultaneously operation of engine on both fuels is also possible.

Pipelines of gas system are doubled. The inner pipe is gas pipe and outer pipe creates safety space 21. Exhaust fan 22 continuously draws the atmosphere from safety space and gas sensor 23 signals if gas leak occurs.

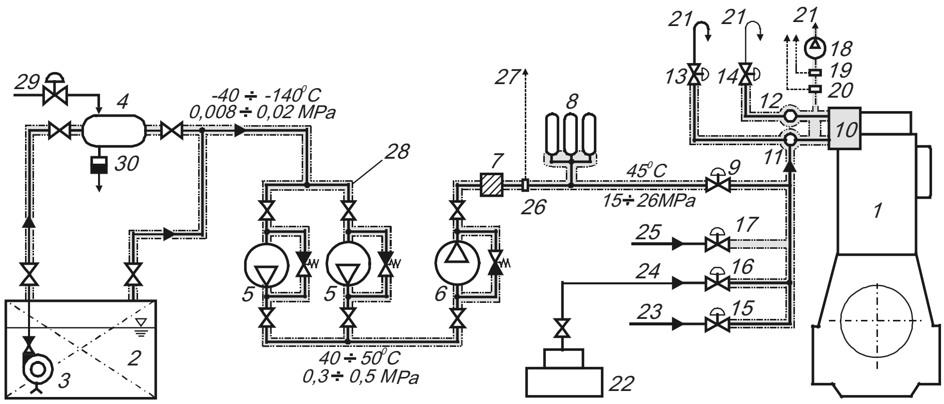

Fig. 4. Slow speed diesel engine gas fuel supply system [1] 1 – low speed diesel engine; 2 – LNG cargo tank; 3 – liquefied gas pump; 4 – vaporiser; 5 – low pressure compressor; 6 – high pressure compressor; 7 – filter; 8 – pressure accumulators; 9 – gas main cut off valve; 10 – gas nozzles unit on engine cylinder head; 11 – gas inlet manifold; 12 – vent manifold; 13 – main vent valve; 14 – auxiliary vent valve; 15 – blow through air inlet valve; 16 – nitrogen inlet valve; 17 – safety space blow through air inlet valve; 18 – safety space exhaust fan; 19 – flow sensor; 20 – gas sensor; 21 – vent; 22 – nitrogen generator; 23 – blow through air inlet; 24 – nitrogen inlet; 25 – safety space blow through air inlet; 26 – pressure sensor; 27 – pressure signal; 28 – safety pipe of gas piping; 29 – heating steam inlet; 30 – condensate outlet

Low speed crosshead diesel engines gas supply system shown in Fig. 4 is more complicated. Because there are no inlet valves in these engines a necessity of direct gas, injection into combustion chambers occurs. It can be executed under high pressure 15-26 MPa by special construction of gas nozzles. Additional multistage high-pressure compressors 6 should be used in the supply system. Initial part of the system is similar to the same in medium speed diesel engines gas supply system. Operation of supply system, kind of fuel change over and pilot dose of liquid fuel is automatically controlled.

Supply of marine engines with natural gas is possible not only on LNG carriers but also on other ships for example ferries, container ships, tugboats or passenger liners. Dual-fuel technology is easy to apply in medium speed and high speed diesel engines of ship main propulsion as well as in dieselgenerator sets.

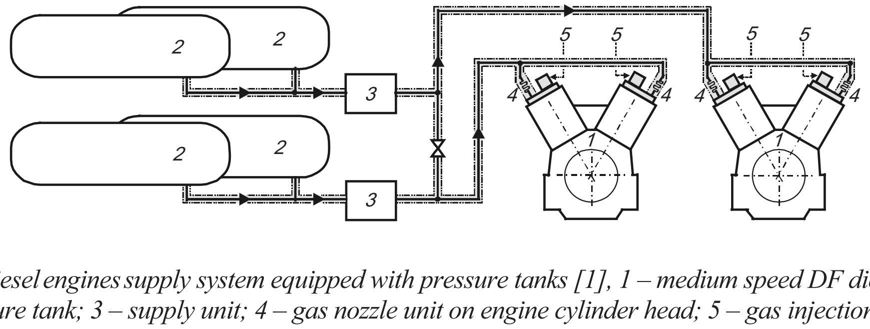

Fig. 5. Gas fuel diesel engines supply system equipped with pressure tanks [1], 1 – medium speed DF diesel engine; 2 – gas fuel pressure tank; 3 – supply unit; 4 – gas nozzle unit on engine cylinder head; 5 – gas injection control signal

The system of diesel engines supply with natural gas is shown in Fig. 5. Natural gas is supplied on board in liquid form and stored under pressure about *1.0 MPa* in storage tanks 2. Engines are supplied via supply unit 3, where vaporisers, process control equipment, automation equipment and leak detectors are located. Pressure tanks allow resigning from supply compressors use. An additional fitment of the system can be equipment-condensing boil off gas in tanks to keep safety pressure inside. Compact construction minimises space occupied by the system.

3. Logistic problems of natural gas use on seagoing ships in the future

Application of gas fuel on ships other than LNG carriers creates necessity of world wide net of gas bunker stations.

Gas propulsion is profitable on ships operating mainly on ECA (Emissions Control Areas) e.g. Baltic Sea. Thus, the countries of ECA region are interested in gas bunker stations establishment. If the ship operates mainly in intercontinental trade outside of ECA areas dual-fuel engines investment profit can be problematic.

So far, the majority of European countries do not have port gas bunkering infrastructure. Norway is an exception where gas fuelled ferries is in operation for ten years. Some ferries are built by Remontowa Shipbuilding in Gdansk Poland. Due to developed infrastructure Norwegian gas, fuelled ships can bunker in each larger Norway port. Gas fuel bunker station is also in the port of Hamburg.

Within Trans European Core Network program European Union plans construction of 139 LNG, bunker stations until the year 2020. Infrastructure necessary for gas fuel bunkering is very expensive. It comes from a number of requirements due to storage safety reasons. Natural gas should be stored under high pressure and cooled to very low temperature. That is why storage of natural gas is difficult.

4. Conclusions

Brought into effect regulations force ship owners to use means for reduction of atmosphere harmful substances emission. One of the most effective solution is use of natural gas for seagoing ships fuelling.

Presently construction and operation of ships driven by dual-fuel engines is considerable more expensive than ships driven by conventional engines. It is possible that use of spark ignited engines instead; dual-fuel engines will reduce expenses. Spark ignited engines do not need pilot dose of liquid fuel. It simplifies ship fuel supply system, as it comprises only gas storage tanks and gas fuel supply system.

Development trends of ship propulsion system it can be forecasting by statement that natural gas will be widely used as marine fuel in the future. Natural gas will be especially applied on areas of restricted regulations concerning atmosphere harmful substances emission. That is why ship owners consider now adopting presently used diesel engines for natural gas combustion, and on growing number of new built ships; dual-fuel engines are installed.

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