Scientific Journals
Maritime University of Szczecin

Zeszyty Naukowe
Akademia Morska w Szczecinie

2013, 36(108) z. 2 pp. 190–195
ISSN 1733-8670

2013, 36(108) z. 2 s. 190–195

The possibilities of limiting the toxic compound emission from Diesel engines and boilers during ship's stay in harbour

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Key words: ship's power plant, environment protection, toxic compound emission, ship's power and boiler plants

Abstract
During their stay in harbours the ships generate the electric energy and heat for their needs most frequently by use of their own power and boiler plants through Diesel generating sets and oil fired boiler. The operation of this machinery causes the toxic compound emission to the atmosphere. In this article the possibilities are presented of limiting this emission through such activities as supplying the ship with the energy from the shore power network, from barge-situated power plant provided with the Diesel generating sets supplied with LNG, and in case of the boiler plant through the application of the liquid or solid biofuel. There are also presented some selected results of the simplified comparative analysis of the emission levels with the various methods of generating the electric energy and heat during ship's stay in harbour.

Introduction

The introduction of the Emission Control Areas (ECA) by the International Maritime Organisation (IMO), as well as the implementation of requirements for the reduction of the emission of toxic compounds in the European Union ports, nowadays constitute a major challenge for the shipping industry. The permissible NO_x emission limits – Tier III standard which had been assumed to come in force as of 01.01.2016 in these areas is shown in table 1.

Table 1. The existing and future NO_x emission limits acc to MARPOL convention Annex VI [1]

Engine rpm [min^{-1}]	NO_x [g/kWh] emission limit	
	Tier II	Tier III*
$n < 130$	14.4	3.4
$130 \leq n < 2000$	$44 \cdot n^{(-0,23)}$	$9 \cdot n^{(-0,2)}$
$n \geq 2000$	7.7	1.96

* applicable only to NO_x emission control areas (ECA)

The introduction of Tier III as of 01.01.2016 has been made subject to the availability of the technologies enabling such NO_x emission limiting. In conformity with the IMO study and the information from the first half of 2013 the date of Tier III enforcement shall be postponed until 01.01.2021. The incorporation of the relevant modification to the regulations has been announced to take place at the meeting of Marine Environment Protection Committee MEPC 66 in 2014 [2]. This means that still for some time the Tier II limitation will continue to be applicable in this area in the same manner as for the remaining areas.

Whereas in relation to the sulphur oxides their permissible emission is limited by the introduction of the limit of the sulphur content in fuel. The permissible limit of the sulphur content in fuel within the SO_x control areas (SECA – SO_x Emissions Control Areas), which shall come in force since 01.01.2015, is 0.1%. Alternatively, it is allowed to apply the systems for the continuous reducing and monitoring of SO_x content in the exhaust gas, at least down to the level corresponding to the application of fuel of the permissible sulphur content.

In general the European Union Member States comply with the IMO regulations, however, the stricter regulations in respect of the sulphur oxides in ports have come in force earlier, because already since 1 January 2010. They apply in the ports throughout all the community and provide for the application of fuels with sulphur content not exceeding 0.1% per weight unit for the sea-going and inland navigation ships during their stay in ports. In compliance with the regulations the ship moored in harbours is such ship which is safely moored or at anchor alongside in port during her unloading or loading operation, as well as during operations not related with the cargo itself. The regulations also cover the period of ship's stay in shipyard, both at its quay and while in dry-dock. The compliance with the requirements is not obligatory for the time of manoeuvring, nevertheless they must be complied with as soon as possible after reaching the harbour and as late as possible before departing from the harbour.

For the purpose to reduce the CO_2 emissions since 1 January 2013 all the newly built ships larger than 400 GRT must have specified Energy Efficiency Design Index (EEDI), whereas all the ships, i.e. the newbuildings and those built before that date are covered by the Ship Energy Efficiency Management Plan (SEEMP) ensuring the optimum ship operation [2]. This obligation applies for the time being to only 7 ship types, i.e. bulk carriers, gas carriers, tankers, containerships, general cargo ships, reefer ships and the combined bulk carriers-tankers.

Moreover, there is a voluntarily determined Energy Efficiency Operational Indicator (EEOI) allowing the current evaluation of the ship's transport effectiveness which might be supplementary for SEEMP [3].

EEOI is defined as:

$$\mathrm{EEOI} = \frac{\sum_{j} FC_j \cdot C_{Fj}}{m_{\mathrm{cargo}} \cdot D} \quad (1)$$

where:

- FC – the mass of the fuel consumed during the voyage (sailing and stay in harbour) by main and auxiliary engines, boilers and incinerator;
- J – fuel kind;
- C_{Fj} – conversion coefficient expressed by the ratio of the mass of CO_2 formed from burning of the consumed fuel kind j;
- m_{cargo} – mass of the cargo carried (tonnes) or the work done (number of TEU or passengers) or capacity (GT) for passenger ships;
- D – distance in sea miles at which the cargo has been carried or the transport work done [4].

Achieving of the small EEOI value is possible through any efforts favouring the reduction of fuel consumption by ships, also in port. The primary actions reducing the EEOI, but also EEDI, while sailing comprise e.g. utilisation of the waste heat from exhaust gas, but also the application of the wind power or solar energy. The LNG application as fuel on ships is also strongly encouraged by the European Union. EU assumes the limitation of the greenhouse gases emission from transport means, including ships, by year 2050 by the value of 60%. These activities support not only the reduction of CO_2 emission, but also NO_x and SO_x emissions.

For the operational condition such as stay in harbour the emission limitation can be achieved by utilisation of the shore power or the power from barge-based power plant supplied with LNG, and in case of boilers by the application of biomass as the fuel. The existence of several possible solutions for this purpose makes one pose a question which of those solutions affects the natural environment in the least.

The determination of the emissions from ships supplied from own power plant during stay in harbour

The simplified analysis using the example of two passenger-car ferries has been conducted for the evaluation of the toxic compound emission from ships alongside in port. The basic ship data are presented in table 2. In both instances the power is generated by the power plants consisting of Diesel generating sets.

Table 2. The selected technical data and operational measurements taken during port operations for the ferries used as examples [5]

Item	Ship's parameters	Unit	Technical data	
			Ferry I	Ferry II
1	Year built	–	1990	1986
2	Type	–	RO-PAX	COMBI
3	Register size	GT	18653	22874
4	Auxiliary engine type	–	Mitsubishi S6R2 MPTK	Wärtsilä – Sulzer 6R 32 BC
5	Auxiliary engine power output	kW	610	2045
6	Generator power output	kVA	700	2430
7	Average fuel consumption by the generating sets while in port	kg/h	77,65	165
8	Average load of generating sets while in port	kW	350	650

The choice of ferries for the purpose of the analysis is the effect of their operational characteristics. Since they are vessels cyclically calling at the same ports and with strictly defined time schedule of calls, these are very good material for studying in view of the repeatability of the operational conditions.

The emission volumes during ship stay in harbour have been estimated basing on the measurements of the generating sets fuel consumption and loading. The readouts have been taken while alongside at the terminal during unloading and loading. The period of taking the measurements can theoretically overlap the period when given vessel could be using the shore power.

The manner of determination of the emissions of the individual toxic compounds has been presented in more detail in [5]. On the basis of the measurement data of the average energy consumption during stay in harbour and the fuel consumed during that time the specific emission *m* has been defined for each ship in compliance with the relation (2).

$$m = \frac{M \cdot \sum G}{\sum N} \ [\text{g/kWh}] \qquad (2)$$

where:

M – mass emission of the compound, g/kg$_{fuel}$;
G – hourly fuel consumption while in port, kg/h;
N – average load of the marine power plant, kW.

The table 3 shows the ship's fuel composition assumed for the analysis with the currently permissible sulphur content of 0.1%. The lower calorific value calculated basing on the fuel composition by the application of the Mendeleyev's formula is 41.7 MJ/kg.

Table 3. Percentage and composition by mass of the fuel as applied for calculations [5]

Item	Fuel component	C	H_2	O_2	N_2	S	A[1]	W[2]
1	Percentage fraction [%]	85.4	12.3	1.0	0.5	0.1	0.1	0.6
2	Mass fraction [m/m]	0.854	0.123	0.010	0.005	0.001	0.001	0.006

[1] ash; [2] water

The volume of the solids emission from the medium-speed engines has been assumed according to the literature as the constant value and reduced to soot emission [6]. The calculation results are specified in table 4.

Table 4. Specific emission from the marine power plant for the selected ferries

Compound	CO_2	SO_2	NO_x	CO	Particulates
Emission for power plant of ferry I [g/kWh]	721.036	0.466	13.089	1.775	0.050
Emission for power plant of ferry II [g/kWh]	825.000	0.533	14.977	2.031	0.050

The evaluation of the emissions with the ship supplied by shore power

The ship connecting in port to the shore power network influences significantly the emission volume and its place of occurrence. The emission in the port itself is totally eliminated; the emission being transferred to the area of the shore power plant which is often situated some distance apart from the city agglomeration. In this context it is also of immense significance which fuel is used to supply given power plant. As the example for the comparison there have been taken two different power plants comprised within the complex of the Dolna Odra Power Plants, i.e. Dolna Odra Power plant and Szczecin Power Plant. The former is the typical coal-based plant working on hard coal. 8.7% biomass is added to coal in this power plant to improve the CO_2 emission indicators [7]. Nevertheless this kind of power plant is allegedly the least environment-friendly all the same. The latter is the ecological power plant supplied exclusively with biomass using the fluidised-bed boiler. Thus, there are two extreme cases of power plant arrangements in terms of environment pollution. For the Dolna Odra Power Plant the assumed specific emission is that calculated basing on the emission and energy generated volume data for 2009 whereas for Szczecin Power Plant there have been given the data published in the plant documentation [5, 8]. The specific emission values from both these power plants are given in table 5.

Table 5. Specific emission for Dolna Odra and Szczecin Power Plants [5, 8]

Compound	CO_2	SO_2	NO_x	CO	Particulates
Specific emission [g/kWh] Szczecin Power Plant	0[1]	0.061	1.4	–	0.063
Specific emission [g/kWh] Dolna Odra Power Plant	866.9	1.221	1.625	0.086	0.097

[1] on account of burning biomass in 100% the 0 value has been assumed

As evidenced in the data shown in the table the application of the technology of fluidised biomass burning decidedly brings down the emissions of the individual compounds. In particular, the CO_2 emission is limited completely since its assumed circulation in the atmosphere in the closed cycle with biomass burning, as well as the emission of the sulphur oxides is largely reduced.

However, it should be taken into consideration that in reality the ships connected to shore power utilise the electric energy generated simultaneously from several sources including the wind power plants where no toxic compounds are generated.

The marine power plants in question produce worse indicators as compared to those from coal-based power plant only in respect of the nitrogen and carbon oxide emissions. In comparison to the biomass-based power plant the marine plant prevails only in terms of the solids, which is the effect of the application of the liquid fuel.

Ship powered by the LNG-supplied Diesel generating sets

The application of the natural gas as a fuel on ships is one of the possibilities to achieve considerably lower toxic compound emissions than with the hydrocarbon fuel burning. Then the emissions of SO_x and particulates are practically eliminated, whereas NO_x emission, while burning this gas in marine four-stroke engine, can be reduced by 90% [9]. Since the chief component of natural gas is methane (CH_4) characterised by the most favourable ratio of the number of hydrogen atoms to the carbon atoms amongst all hydrocarbons, then CO_2 emission is less. The bigger calorific value is also of some importance, because it reaches 50 MJ/kg which gives ca 10% more energy from 1 kg fuel. In the effect burning the natural gas allows to achieve ca 25% less emission of CO_2 in comparison to burning marine Diesel oil (MDO). A disadvantage of natural gas is its small density which in liquefied state at –163°C and ambient pressure amounts to 450 kg/m^3. It would take double or threefold volume of fuel storage tanks as compared to MDO for making the same distance. Thus, LNG as the fuel is primarily used in shipping for the ships of low endurance, such as for instance ferries.

Owing to the small emission while LNG burning it is particularly justifiable to use this fuel to generate electric energy for the ship's needs while alongside in port. An arrangement worthy of popularisation is the utilisation of barge-situated power plants provided with LNG supplied generating sets. The barges moored to ships while in harbour power the ships in the same way as it is done in case of shore power connection. Thus, the operation of the marine Diesel generating sets using the liquid hydrocarbon fuel is eliminated and substituted by the generating sets on barge using LNG. Such arrangement is proposed in the port of Hamburg by the Owner of passenger ships AIDA Cruises together with the Messrs Becker Marine Systems. The first vessels owned by this ship owner are to be powered from the barge while in port in 2013 [10].

To demonstrate the benefits of such solution it has been assumed that the ferries under investigation are powered from such barge power plant. To simplify the analysis it is assumed that the barge engine efficiencies are the same as those of auxiliary engines on ferry I. The ferry II engines have lower efficiency. The barge engine power load has been assumed the same as for given ferry, respectively. It has been assumed that LNG lower calorific value in barge tanks amounts to 50 MJ/kg. The LNG consumption and total CO_2 emission have been calculated for the barge engines correspondingly to the liquid fuel and the results are shown in table 6. CO_2 emission while LNG burning has been determined basing on the guidelines assumed in document [4]. It is assumed that the carbon mass share in LNG amounts to 0.75 and therefore the conversion coefficient for fuel to CO_2 in mass amounts to 2.75 Mg CO_2/l Mg LNG.

Table 6. The gas consumption and CO_2 emission applicable to the barge power plant supplying selected ferries

Parameter	Ferry I	Ferry II
LNG consumption [kg/h]	64.76	120.2
CO_2 specific emission [g/kWh]	508	508
Total CO_2 emission [kg/h]	177.8	330.2

The evaluation of boiler emissions

The regulations applicable to the marine boiler emissions are not that restrictive as those in case of engines. In principle, they apply to boilers indirectly by the order to use in ports and SECA areas the fuels of sulphur content below 0.1%. Boilers, on other hand, are considered under the evaluation of the EEOI expressed by relation (1). It implies that the boilers to be installed should be characterised by the low fuel consumption. So far, there are no regulations regarding the NO_x emissions by ship's boilers. It may be attributed to the fact that the specific emission of this compound is relatively low since normally while at sea only exhaust heat boilers are in use. However, to get the problem recognised better it may be worthwhile to evaluate the actual boiler emission at the example of the analysed vessels.

Both ferries while alongside in port generate steam in oil-fired boilers. In each case the fuel of sulphur content under 0.1% is used in compliance with respective regulations. For the calculations of the individual compound emissions the fuel of the same contents has been assumed as it is burned in the auxiliary engines as shown in table 3. The table 7 states the nominal fuel consumption and boiler heating capacity on both ferries and the emission calculated for individual compounds. The calculations of CO_2 and SO_2 emissions have been made basing on formulae for the determination of the volume of exhaust gas components and their known density [11]. For compounds like NO_x and CO, as well as in respect of the emission of solids the indices for pollutant emission from burning have been applied as elaborated by Krajowy Ośrodek Bilansowania i Zarządzania Emisjami (National Centre for Balancing and Emission Management) for the boilers of nominal heating capacity less than 5 MW [12].

Table 7. Fuel consumption, heating capacity and specific emission for the boilers of selected ferries

Parameter	Ferry I	Ferry II
Boiler heating capacity [kW]	980	1160
Fuel consumption [kg/h]	95	110
CO_2 specific emission [g/kWh]	305	298
CO_2 total emission [kg/h]	299	345
CO specific emission [g/kWh]	0.058	0.056
SO_x specific emission [g/kWh]	0.19	0.18
NO_x/NO_2 specific emission [g/kWh]	0.232	0.227
Specific emission of particulates [g/kWh]	0.039	0.038

Actually, the results confirm minor specific emission of the nitrogen oxides while burning fuel in boilers in comparison to burning in engines. The case is similar with the specific emissions of the remaining exhaust gas components which results from the significantly large efficiency of boilers.

Conclusions

The analysis performed provides certain view of the volume of emissions from ship alongside in harbour in case of various modes of her powering. Generation of the electric energy in each case is involved with toxic compound emissions. To make the objective choice of the best variant it would be recommendable to consider the environmental harm and oppression of the individual compounds by assigning to them for instance the respective affect importance degrees including the costs aspects.

It could be assumed that the comparison of the emission volumes from any conventional coal-based shore power plant with the marine power plant based on Diesel generating sets supplied with low sulphur content fuel would give similar results. Better effects would be likely to achieve, if the shore power plant used clean carbon technologies such as fluidised-bed burning or sequestration of carbon dioxide. However, connecting the ships to shore power is by all means recommendable in the ports of countries with the considerable share of the nuclear power engineering and renewable energy sources.

It is worthwhile to pay attention to CO_2 emission in all cases in terms of possibility of achieving the advantageous value of EEOI. Figure 1 shows the CO_2 hourly emission related with the electric energy generated in various manners and emission of this compound from boilers during stay of the selected ferries in ports.

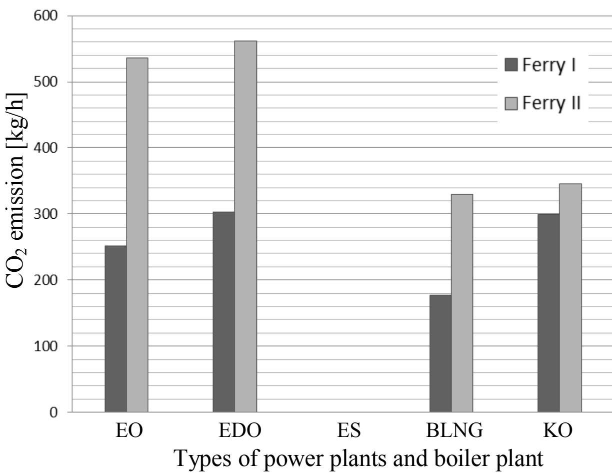

Fig. 1. Specification of the hourly CO_2 emission during ferry stay in port with various manners of electric energy generation and generation by boilers; EO – marine power plant; EDO – Dolna Odra Power Plant; ES – Szczecin Power Plant; BLNG – LNG-Fuelled Power Plant Barge; KO – marine boiler plant

The comparison proves that the least advantageous manner in the analysed cases is the utilisation of the shore power based on coal power plant. Very favourable is the case of the powering with the electric energy generated on barge with the Diesel generating sets using LNG and this is the solution deserving stronger encouragement, also in terms of minor emission of the remaining compounds. The comparison of CO_2 emission from power plant and boiler plant at the example of the vessels analysed indicates that the total emission of this compound from boiler plant may exceed even the CO_2 volume emitted from power plant. In case of boiler plant it might be justifiable, following the example of the power plant, to substitute it with the shore heat source or for instance boiler plant installed on barge and supplied e.g. with biomass in the pellets form [12]. Another beneficial solution could be a barge with LNG supplied cogeneration system.

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