MARINE ENGINES OF NATO NAVIES AND ECOLOGICAL PROBLEMS OF THEIR EXPLOITATION

Malgorzata Pawlak
Leszek Piaseczny

Naval University of Gdynia
ul. Smidowicza 69, 81-103 Gdynia

Abstract

Imposing the legal regulations aims at extorting restrictions of harmful substances in marine engines exhaust gases emissions. An Annex VI of MARPOL73/78 Convention, being ratified in 2005, lays commercial ships under an obligation of the reduction of emissions of sulphur and nitrogen oxides that are formed when combusting marine fuels. And although navy vessels are excluded from performing that obligation, a great number of studies on emission reduction methods applicable at NATO navies have been carried out. It is worth noticing that in relation to the sulphur level in marine fuel, the NATO ships fulfil the requirements specified by Annex VI, because the fuel used by naval ships is of low sulphur level. However, the admissible NO_x emission levels in naval ships exhaust gases is much higher comparing to the one in commercial ships.

Keywords: *marine engines, exhaust gas emission, NATO navies*

1. Introduction

Environmental protection issues are important for NATO Nations. A great number of studies and research have been carried out, many reports and scientific publications have been prepared. One of the main tasks of Special Working Group for Marine Environment Protection (SWG/12), of the NATO Naval Armament Group (NNAG) is implementation of international organizational, technical and legal standards concerning marine environment protection against pollution from ships.

In 1995, Special Working Group SWG/12 conducted a study for the „NATO Environmentally Sound Ship of the 21st Century". Its objectives were to determine the methods of effective shipboard waste management and treatment to be fully compliant with current and future regulations for the protection of the maritime environment. The document deserves attention as historically the first study in NATO concerning maritime environment protection issues.

Gaseous wastes can be divided into four key groups:

- exhausts from marine main diesel engines (main and auxiliary);
- exhausts from marine gas turbine engines and steam boilers (main and auxiliary);
- ozone depleting substances (halons and freons);
- volatile organic compounds (VOCs).

In the paper, only two first categories will be discussed, i.e. exhausts from marine diesel engines (DE) gas turbine engines (GT) and steam boilers (ST).

2. Gaseous emissions of engine exhaust gases in the US Navy

U.S. Navy estimated the exhaust gases emissions resulting from burning the hydrocarbon fuel on American vessels (for the year 1994), such as: nitrogen oxides (NO_x), sulphur oxides (SO_x), carbon dioxide (CO_2), carbon monoxide (CO), unburned hydrocarbons (HC) and particulate matter (PM). The evaluation was encompassing 44 ship classes and 256 ships (Table 1).

Tab. 1. Exhaust gases emission estimates in the U.S. Navy marine engines in 1994 [1]

Class	No. of ships	Main propulsion		Auxiliary propulsion		Estimated total class exhaust emissions [t/yr]					
		Type	Power [kW]	Type	Power [kW]	NO_x	SO_x	CO_2	CO	HC	PM
AD37	2	ST	29 800	ST	NA	57.8	176.5	57 219	68.5	5.6	4.0
AD41	4	ST	59 700	ST	NA	97.2	296.2	96 040	137.2	11.3	8.0
AE21	2	ST	23 900	ST	NA	28.9	86.6	28 083	54.9	4.5	3.2
AE23	2	ST	23 900	ST	NA	17.8	53.7	17 424	54.9	4.5	3.2
AE27	7	ST	114 800	ST	NA	181.2	543.4	176 181	263.9	21.7	15.3
AFS1	3	ST	49 200	ST	NA	59.0	175.9	57 024	113.1	9.3	6.6
AO177	5	ST	89 500	ST	NA	149.2	446.8	144 856	205.7	16.9	12.0
AOE1	4	ST	298 300	ST	NA	204.0	612.2	198 477	685.6	56.3	39.8
AOR1	5	ST	119 300	ST	NA	173.5	518.7	168 188	274.2	22.5	15.9
AR5	1	ST	8 600	ST	NA	34.0	101.9	33 030	19.8	1.6	1.1
AS 33	2	ST	29 800	ST	NA	26.9	82.3	26 670	68.5	5.6	4.0
AS 36	2	ST	29 800	ST	NA	18.2	55.4	17 972	68.5	5.6	4.0
AS 39	3	ST	44 700	ST	NA	24.2	73.6	23 856	102.7	8.4	6.0
CG16	2	ST	126 800	ST	NA	48.3	144.6	46 873	291.4	23.9	16.9
CG26	3	ST	190 200	ST	NA	45.2	137.2	44 483	437.2	35.9	25.4
CV59	2	ST	417 600	ST	NA	349.1	1040.5	337 355	959.8	78.8	55.8
CV63	3	ST	626 400	ST	NA	734.5	2191.8	710 655	1439.7	118.1	83.7
CV67	1	ST	208 800	ST	NA	0.0	0.0	0.0	0.0	0.0	0.0
FF1052	8	ST	208 800	ST	NA	32.5	98.4	31 900	479.9	39.41	27.9
LCC19	2	ST	32 800	ST	NA	58.1	175.6	56 926	75.4	6.2	4.4
LHA1	5	ST	261 000	ST	NA	296.1	884.9	286 898	599.9	49.2	34.9
LHD1	2	ST	104 400	ST	NA	148.8	444.2	144 031	240.0	19.7	13.9
LKA113	1	ST	16 400	ST	NA	0.6	1.8	579	37.7	3.1	2.2
LPD1	1	ST	17 900	ST	NA	19.8	60.1	19 489	41.1	3.4	2.4
LPD4	11	ST	196 900	ST	NA	378.6	1135.2	368 075	452.6	37.1	26.3
LPD7	1	ST	17 900	ST	NA	20.4	61.3	19 887	41.1	3.4	2.4
LPH2	5	ST	85 800	ST	NA	164.6	491.9	159 475	197.2	16.2	11.5
LSD 36	5	ST	89 500	ST	NA	144.0	430.8	139 682	205.7	16.9	12.0
MCSC	1	ST	17 900	ST	NA	1.6	4.8	1 541	41.1	3.4	2.4
DDG51	2	GT	149 100	GT	15 000	345.9	296.7	98 567	289.3	18.4	18.5
DDG993	4	GT	238 600	GT	24 000	386.6	386.1	127 939	439.9	35.3	24.1
DD963	31	GT	1 849 400	GT	186 000	3198.5	3349.3	1 110 327	3803.6	306.6	208.9
CG47	25	GT	1 491 400	GT	165 000	3153.6	3120.0	1 039 093	3455.1	216.6	195.5
FFG7	51	GT	1 521 300	DE	204 000	5003.1	2421.6	790 535	4078.2	413.2	254.1
ASR7	1	DE	2 200	DE	NA	20.8	5.2	1 877	3.5	0.4	0.6
MSO427	4	DE	6 800	DE	NA	17.5	2.6	950	10.5	2.8	0.4
AS 31	2	DE	17 400	DE	6 200	321.5	26.0	9 385	436.3	23.0	2.8
ASR21	1	DE	4 500	DE	2 000	212.5	26.0	10 679	436.3	23.0	2.8
ATS1	3	DE	13 400	DE	3 600	320.6	43.6	15 732	45.1	9.3	3.9
ARS38	5	DE	9 100	DE	4 500	190.6	64.2	23 123	20.5	2.5	6.8
ARS50	4	DE	12 500	DE	9 600	336.3	103.3	37 233	30.7	9.0	12.1
MCM1	10	DE	17 900	DE	13 000	255.9	45.2	16 280	59.6	26.3	5.0
LST1179	10	DE	123 000	DE	24 000	2267.5	493.1	177 662	490.1	68.5	42.9
LSD 41	8	DE	220 100	DE	45 600	2986.3	295.7	106 549	213.3	121.0	24.2
Total	**256**		**9 217 100**			**22 531.3**	**21 204.9**	**6 978 802**	**21 469.4**	**1 904.4**	**1 247.8**

(ST – steam turbine, DE – diesel engine, GT – gas turbine engine, NA – data not available)

To estimate exhaust emissions, the U.S. Navy used two general methodologies: a fuel-based method and an operating profile-based method [2,3]. Due to the fact that operating power profiles and individual boiler emission factors were not available for steam turbine powered ships, estimation of the exhaust emissions for these vessels was made on the basis of the amount of fuel consumed by each ship, in compliance with the U.S. EPA fuel-based emission factors. For each class of diesel powered or gas turbine powered ships and for each pollutant type, an operational based emission factor (including the generator engines) was developed, based on the operating power profile and the emission data of installed engines. This factor was multiplied by the number of underway hours per year for each ship. In addition, there were estimated the emissions for the generators running in port or at anchor, when the generators were required to be operated.

3. Exhaust gas emissions from marine engines of NATO Navies in 1995-96

Table 2 shows the installed propulsion power distribution in the ships of different NATO Navies in the years 1995-96.

Tab. 2. Propulsion power distribution summary in selected NATO Navies in 1995-96 [1]

NAVY	Total Power [MW]	DE						GT				ST			
		<1	1-5	5-10	10-20	>20	**Total**	<10	10-20	>20	**Total**	<10	10-20	>20	**Total**
BELGIUM	98	7	34	0	0	0	**41**	0	57	0	**57**	0	0	0	**0**
CANADA	772	7	32	72	0	0	**111**	0	0	502	**502**	0	47	112	**159**
DENMARK	333	17	79	37	0	0	**133**	144	55	0	**199**	0	0	0	**0**
FRANCE	1247	45	138	344	117	64	**707**	0	0	69	**69**	0	0	471	**471**
GERMANY	1307	13	245	343	208	0	**808**	0	0	342	**342**	0	0	157	**157**
GREECE	1110	24	83	174	203	0	**485**	0	0	243	**242**	5	0	377	**382**
ITALY	1310	25	100	255	62	0	**442**	19	22	664	**705**	0	0	162	**162**
NETHERLANDS	755	10	35	102	15	0	**162**	0	0	593	**593**	0	0	0	**0**
NORWAY	250	6	72	113	0	0	**1910**	0	0	0	**0**	0	59	0	**59**
PORTUGAL	345	16	45	108	59	0	**228**	0	0	119	**119**	0	0	0	**0**
SPAIN	645	20	108	47	96	0	**271**	4	0	218	**222**	0	33	129	**162**
TURKEY	1129	41	78	179	183	98	**579**	10	18	45	**73**	0	0	478	**478**
UK	2097	44	233	130	152	0	**558**	0	0	1452	**1452**	0	87	0	**87**
US	10925	205	76	385	137	248	**1051**	28	936	6169	**7133**	0	858	185	**2742**
TOTAL	**22332**	**480**	**1358**	**2289**	**1232**	**410**	**5767**	**205**	**1088**	**10416**	**11709**	**5**	**1084**	**1770**	**4559**

As it results from the table, those days all the Navies had diesel powered ships and nearly all (excluding Norway) had gas turbine powered ships. Some of them (Belgium, Denmark, Netherlands and Portugal) did not have steam propulsion installed.

4. Estimation of the NATO Navies future exhaust gas emissions

It is possible to estimate the future exhaust emissions from NATO marine engines. There are two factors that are expected to influence the level of those emissions.

The first one involves the changes in exhaust emission levels of new engines which will be driven mainly by changes in emission regulations. Some changes in marine engine regulations will undoubtedly affect the ship exhaust emission levels directly. An example of such types of changes are the regulations of the International Marine Organisation (IMO), concerning the acceptable levels of NO_x and SO_x emissions by marine diesel engines. Other expected changes are those in regulations for other applications, such as land based power generations or mechanical drive applications, which will affect the ship exhaust emission levels indirectly if the same engine model is used both in land and marine applications. This is generally the case for gas turbines.

The second factor that will influence future naval ship exhaust emission levels is the changes to the force structure of the navies, such as decrease in overall number of ships, modernisation of some vessels by changes in propulsion power types or lowering the power levels, or replacement of older ships with the more modern ones.

To illustrate the changes in emission levels caused by the above mentioned factors, there was analysed some data of the future exhaust emission estimates for the U.S. Navy in 1994. Table 3 contains the 1994 U.S. Navy ship exhaust emission estimates previously shown in Table 1, together with revised estimates to account for changes expected to occur by 2010.

Tab. 3. Exhaust emission levels estimated for the U.S. Navy engines in 2010 [1]

U.S. Navy Class	No. of ships	Main propulsion		Auxiliary propulsion		Estimated total class exhaust emissions in 2010 [t/yr]					
		Type	Power installed [kW]	Type	Power installed [kW]	NO_x	SO_x	CO_2	CO	HC	PM
AD 37	2	ST	29 800		NA	57.8	176.5	57 219	68.5	5.6	4.0
AD 41	4	ST	59 700		NA	97.2	296.2	96 040	137.2	11.3	8.0
AR 8	1	ST	8 600	ST	NA	34.0	101.9	33 030	19.8	1.6	1.1
AS 33	2	ST	29 800	ST	NA	26.9	82.3	26 670	68.5	5.6	4.0
AS 36	2	ST	29 800	ST	NA	18.2	55.4	17 972	68.5	5.6	4.0
AS 39	3	ST	44 700	ST	NA	24.2	73.6	23 856	102.7	8.4	6.0
Subtotal 1	**14**		**202 400**			**258.4**	**785.8**	**254 787**	**465.2**	**38.2**	**27.0**
Subtotal 1 rev.	**13**	**less AR 5**	**193 800**			**224.4**	**684.0**	**221 757**	**445.4**	**36.5**	**25.9**
AE21	2	ST	23 900	ST	NA	28.9	86.6	28 083	54.9	4.5	3.2
AE23	2	ST	23 900	ST	NA	17.8	53.7	17 424	54.9	4.5	3.2
AE27	7	ST	114 800	ST	NA	181.2	543.4	176 181	263.9	21.7	15.3
AFS 1	3	ST	49 200	ST	NA	59.0	175.9	57 024	113.1	9.3	6.6
AO177	5	ST	89 500	ST	NA	149.2	446.8	144 856	205.7	16.9	12.0
AOR1	5	ST	119 300	ST	NA	173.5	518.7	168 188	274.2	22.5	15.9
Subtotal 2	**24**		**420 600**			**609.6**	**1825.1**	**591 756**	**966.7**	**79.3**	**56.2**
Subtotal 2 rev.	**18**	**1/2 GT**	**420 600**			**851.9**	**1472.3**	**481 008**	**997.0**	**81.8**	**57.9**
AOE 1	4	ST	298 300	ST	NA	204.0	612.2	198 477	685.6	56.3	39.8
Subtotal 3	**4**	**No change**	**298 300**			**204.0**	**612.2**	**198 477**	**685.6**	**56.3**	**39.8**
CG16	2	ST	126 800	ST	NA	48.3	144.6	46 873	291.4	23.9	16.9
CG26	3	ST	190 200	ST	NA	45.2	137.2	44 483	437.2	35.9	25.4
FF1052	8	ST	208 800	ST	NA	32.5	98.4	31 900	479.9	39.41	27.9
Subtotal 4	**13**		**525 800**			**126.0**	**380.2**	**123 257**	**1208.5**	**99.2**	**70.2**
Subtotal 4 rev.	**9**	**only GT**	**525 800**			**226.2**	**233.2**	**77121**	**1284.2**	**105.4**	**74.6**
CV 59	2	ST	417 600	ST	NA	349.1	1040.5	337 355	959.8	78.8	55.8
CV 63	3	ST	626 400	ST	NA	734.5	2191.8	710 655	1439.7	118.1	83.7
CV 67	1	ST	208 800	ST	NA	0.0	0.0	0.0	0.0	0.0	0.0
Subtotal 5	**6**		**1 252 800**			**1083.6**	**3232.3**	**1 048 011**	**2399.5**	**196.9**	**139.4**
Subtotal 5 rev.	**3**	**1/2 Nuclear**	**626 400**			**541.8**	**1616.2**	**524 005**	**1199.8**	**98.4**	**69.7**
LCC19	2	ST	32 800	ST	NA	58.1	175.6	56 926	75.4	6.2	4.4
LHA1	5	ST	261 000	ST	NA	296.1	884.9	286 898	599.9	49.2	34.9
LHD1	2	ST	104 400	ST	NA	148.8	444.2	144 031	240.0	19.7	13.9
LKA113	1	ST	16 400	ST	NA	0.6	1.8	579	37.7	3.1	2.2
LSD 36	5	ST	89 500	ST	NA	144.0	430.8	139 682	205.7	16.9	12.0
MCSC	1	ST	17 900	ST	NA	1.6	4.8	1 541	41.1	3.4	2.4
Subtotal 6	**16**		**522 000**			**649.1**	**1942.0**	**629 657**	**1199.8**	**98.4**	**69.7**
Subtotal 6 rev.	**12**	**all LHA/LHD**	**626 400**			**741.0**	**2214.0**	**717 826**	**1439.7**	**118.1**	**83.7**
LPD1	1	ST	17 900	ST	NA	19.8	60.1	19 489	41.1	3.4	2.4
LPD4	11	ST	196 900	ST	NA	378.6	1135.2	368 075	452.6	37.1	26.3
LPD7	1	ST	17 900	ST	NA	20.4	61.3	19 887	41.1	3.4	2.4
LPH2	5	ST	85 800	ST	NA	164.6	491.9	159 475	197.2	16.2	11.5
Subtotal 7	**18**		**318 500**			**583.4**	**1748.5**	**566 926**	**732.0**	**60.1**	**42.5**
Subtotal 7 rev.	**12**	**only DE**	**318 500**			**6678.6**	**1522.4**	**550 323**	**1384.2**	**226.5**	**80.4**
DDG51	2	GT	149 100	GT	15000	345.9	296.7	98 567	289.3	18.4	18.5
DDG993	4	GT	238 600	GT	24000	386.6	386.1	127 939	439.9	35.3	24.1
DD963	31	GT	1 849 400	GT	186000	3198.5	3349.3	1 110 327	3803.6	306.6	208.9
CG47	25	GT	1 491 400	GT	165000	3153.6	3120.0	1 039 093	3455.1	216.6	195.5
FFG7	51	GT	1 521 300	DE	204.000	5003.1	2421.6	790 535	4078.2	413.2	254.1
Subtotal 8	**113**		**5 249 800**			**12 069.8**	**9 573.7**	**3 166 461**	**12 086.2**	**990.1**	**701.2**
Subtotal 8 rev.	**113**	**1/4 new GT**	**5 249 800**			**11 390.9**	**9 573.7**	**3 166 461**	**12 086.2**	**990.1**	**701.2**

ASR7	1	DE	2 200	DE	NA	20.8	5.2	1 877	3.5	0.4	0.6
MSO427	4	DE	6 800	DE	NA	17.5	2.6	950	10.5	2.8	0.4
AS 31	2	DE	17 400	DE	6200	321.5	26.0	9 385	436.3	23.0	2.8
ASR21	1	DE	4 500	DE	2000	212.5	26.0	10 679	436.3	23.0	2.8
ATS 1	3	DE	13 400	DE	3600	320.6	43.6	15 732	45.1	9.3	3.9
ARS38	5	DE	9 100	DE	4500	190.6	64.2	23 123	20.5	2.5	6.8
ARS50	4	DE	12 500	DE	9600	336.3	103.3	37 233	30.7	9.0	12.1
MCMI	10	DE	17 900	DE	13000	255.9	45.2	16 280	59.6	26.3	5.0
LST1179	10	DE	123 000	DE	24000	2267.5	493.1	177 662	490.1	68.5	42.9
LSD 41	8	DE	220 100	DE	45600	2986.3	295.7	106 549	213.3	121.0	24.2
Subtotal 9	**48**		**426 900**			**6929.5**	**1105.1**	**399 471**	**1745.8**	**285.7**	**101.4**
Subtotal 9 rev.	**48**	**1/4 new DE**	**426 900**			**6409.7**	**1105.1**	**399 471**	**1745.8**	**285.7**	**101.4**
TOTALS	**256**		**9 217 100**			**22 513.3**	**21 204.9**	**6 978 802**	**21 469.4**	**1 904.1**	**1 247.6**
TOTALS REV.	**232**	**about 2010 r.**	**8 688 500**			**27 288.5**	**19 032.8**	**6 336 449**	**21 248.0**	**1 998.8**	**1 234.7**
% change	**-9.4**	**1994 to 2010**	**-5.8**			**+21.1**	**-10.2**	**-9.2**	**-1.0**	**5.0**	**-1.0**

(ST – steam turbine, DE – diesel engine, GT – gas turbine engine, NA – data not available, rev. – revised estimates)

In making the above projection there were made the following assumptions:

- All estimates in regard to future U.S. Navy force levels and its force structure are based on publicly available information;
- Although over the last decades there has been made a significant reduction in the number of U.S. navy ships, the number of fossil fuelled surface ships is not expected to be reduced substantially below the 1994 level by 2010. However, older ships are expected to be replaced with more modern ships, majority of which will be powered by either gas turbine (GT) or diesel engines (DE). Exceptions to this will be a few (about five) additional steam (ST) powered LHD vessels.

To facilitate predicting force composition changes, the U.S. Navy ships were divided into 9 subgroups, as it is indicated by the subtotals in Table 3. In estimating the change in exhaust emissions for each subgroup, the following rationale was applied:

- Subgroup 1: For this group of ST powered ships, only little change in exhaust emission is predicted.
- Subgroup 2: It is assumed that 12 of 24 ST powered resupply ships will be replaced by 6 new more capable GT powered ships (e.g. of the AOE 6 class). However, the total power level of that 18 ship subgroup will not change.
- Subgroup 3: No change is predicted for these four AOE 1 class ships.
- Subgroup 4: It is expected that these ST powered cruisers and frigates will be replaced by GT powered combatants. It is assumed that a one for one replacement for the cruisers and a one for two replacement for the frigates will take place. The total power will remain the same.
- Subgroup 5: It is expected that three of the six ST carriers will be replaced by nuclear powered carriers.
- Subgroup 6: Nine amphibious ships other than the LHAs and LHDs will be replaced by five additional LHDs.
- Subgroup 7: It is predicted that these 18 ST powered LPDs and LPHs will be replaced by LPD 17 class amphibious assault ships, which will probably be DE powered.
- Subgroup 8: It is estimated that about one-fourth of these GT powered ships will be replaced by new vessels of the same propulsion type.
- Subgroup 9: It is assumed that a one-fourth of these DE powered ships will be replaced by new vessels of the same propulsion type.

The method used to estimate the emissions of replacement ships assumed the following:

- For DE or GT powered ships replacing ST ships, the replaced ships emissions estimates were multiplied by factors based on the ratios of the overall average emission rates for all the 1994 ST, DE and GT powered ships on a per unit installed propulsion power basis.

- All new DE powered ships were estimated as indicating 30% lower NO_x emissions than the DE powered ships from 1994, which is in accordance with the regulations of the VI Annex of MARPOL 73/78 Convention, and one-fourth of new GT powered ships were estimated as indicating 90% lower NO_x emissions than the GT powered ships from 1994, reflecting dry low emission combustors in those engines. No retrofit of dry low emission combustors in existing GT powered ships was predicted.

Analysing the results of obtained data, it can be remarked that:

- The increase in NO_x emissions is primarily due to decrease in the number of steam powered ships being replaced by diesel powered ships.
- The decrease in SO_x and CO_2 emissions, which are directly related to fuel consumption, is due to older steam powered ships being replaced by new, more efficient diesel or gas turbine ships.

These examples show how the changes in exhaust emission levels of new engines, as well as the changes in naval force structures can affect the future exhaust emission levels.

5. Exhaust harmful substances generation rates

From the data concerning the U.S. Navy ships, presented in Table 3, the overall rates of exhaust harmful substances generation were calculated for each type of propulsion – DE, ST and GT. These rates were normalised on a per unit installed propulsion power basis, but include auxiliary engine emissions (Table 4).

Tab. 4. Unit exhaust gas harmful substances emission rates [1]

U.S. Navy propulsion type	**Estimated unit emission rates [t/(MW-year)]**					
	NO_x	**SO_x**	**CO_2**	**CO**	**HC**	**PM**
DE	15.3	2.0	730	4.1	0.75	0.19
GT	2.3	1.8	605	2.3	0.19	0.13
ST	1.0	3.0	965	2.2	0.18	0.13

The rates illustrated in Table 4 are useful for making gross estimates of naval ships emissions but as they include many different ship types with different operating profiles, they should be used only for rough estimations. Also, it ought to be mentioned that all of the U.S. Navy emission estimates were made assuming the use of MIL-F-16884/NATO F76 distillate fuel of 0.5% sulphur content and of a carbon to hydrogen ratio of 1.8, and the SO_x and CO_2 emission rates are directly proportional to fuel consumption rates. However, as operation power profiles were included in the estimating process, the fuel consumption rates for different ship types are not directly proportional to the specific fuel consumption rates of the propulsion engines. For instance, the estimated overall SO_x and CO_2 emission rates for GT powered ships are lower than for DE powered ships, although the unit fuel consumption for DE is generally lower than for GT. It is so, because the majority of GT powered naval ships have a large amount of installed propulsion power (in order to provide a relatively high top speed capability), but most of the time they operate at relatively low speeds, which require only a small percentage of the installed power. Therefore, a typical naval GT average operating power as a percentage of the total installed power is much lower than for a typical naval DE.

For CODOG or CODAG[1] ships, the GT operates at a higher percentage of the installed power rating but generally the operating time is much shorter than for the associated DE, so on a yearly basis, the overall waste generation rates might be expected to be somewhat similar to those for all GT powered ships or all DE powered ships in terms of emissions per year per unit installed power.

---

[1] CODOG or CODAG – Combined Gas Turbine and/or Diesel ships

Since the U.S. Navy estimates did not include any CODOG or CODAG ships, the exhaust emission estimates of NO_x and CO_2 were calculated for an Italian Navy CODOG frigate (Table 5).

Tab. 5. Comparison of exhaust gas harmful substances generation rates [1]

Propulsion type	Estimated unit emission rates [t/(MW-year)]			
	NO_x		CO_2	
	U.S. Navy	CODOG	U.S. Navy	CODOG
DE	15.3	14.2	730	997
GT	2.3	2.0	605	373

Table 6 shows the relative compositions of exhaust gases generated by naval high- and medium-speed DE, GT and ST engines, when using fuel MIL-F 16884H/NATO F76.

Tab. 6. Unit emission of exhaust gases and engine noise [1]

Parameters	Units	DE	GT	ST
NO_x	g/(kW·h)	8 - 15	2 - 5	1 - 4
CO	g/(kW·h)	1 - 1.5	0.1 - 1.5	2
SO_x	g/(kW·h)	3 - 4.5	3 - 4.5	3 - 4.5
HC	g/(kW·h)	0.3 - 0.6	0.3 - 0.6	0.8
PM	g/(kW·h)	0.4 - 0.7	0.2 - 0.4	0.4
Smoke	Opacity [%]	10 - 15	-	-
Noise (level)	dB	90	-	-

6. Conclusion

World-wide trends of decreasing the human harmful influence on the natural, including maritime, environment, do no exclude navies. It can be remarked especially over the past few years. Ratification of the Annex VI of MARPOL73/78 Convention in 2005, lays commercial ships under an obligation of the reduction of emissions of sulphur and nitrogen oxides that are formed when combusting marine fuels. And although navy vessels are excluded from performing that obligation, a great number of studies on emission reduction methods being carried out in many countries (the United States of America, Great Britain, the Netherlands) bear evidence of the opportunities and will to expand those regulations over NATO navies. Moreover, some countries (the United States of America and partly France) have already introduced the obligation of meeting the regulations of MARPOL73/78 Convention, including all its annexes.

In relation to the sulphur level in marine fuel, the NATO ships fulfil the requirements specified by Annex VI, because the fuel used by naval ships is of low sulphur level. The problem appears however when considering admissible NO_x emission levels. The MARPOL Convention regulates the NO_x emission levels for diesel engines, which are commonly installed on commercial vessels, but more rarely on naval ones due to their size and weight. What is more, the MARPOL Convention excludes navies from performing that obligation, so even though admissible sulphur oxides concentration levels in exhaust gases is not exceeded, the nitrogen oxides concentration in exhaust gases of these ships exceeds the admissible levels regulated by the Annex VI. Such a situation occurs not only in Polish Navy, and the problem seems to be world-wide [3,4].

Therefore, do the naval vessels should reduce the exhaust gases nitrogen oxides emission? Taking into account that naval vessels do not operate only in case of war, but also peace (e.g. training), they should be treated as any other vessels and thus, laid under the obligation of protecting the natural environment.

A modern naval ship is the vessel that fulfils not only military requirements, but also integrates up-to-date technologies enabling operating on all water regions, even those requiring severe environmental protection regulations. An interest of NATO navies in this problem shows that they do tend to solve ecological problems of their development.

References

[1] NATO Environmentally Sound Ship of the 21st Century, 1995 NATO Unclassified.

[2] Bergier T., Piaseczny L., *Zakres i warunki badań emisji związków toksycznych w spalinach silników tłokowych napędu głównego okrętów*, Zeszyty Naukowe AMW, Nr 1/136/1998.

[3] Markle S.P., Brown A.J., *Naval Ship Engine Exhaust Emission Characterization*, Naval Engineers Journal, September 1996, s. 37-46.

[4] Schnohr O., Frederiksen P., *NOx optimizing of auxiliary engines 21 st.* Int. Congress on Combustion Engines, Cimac, Interlaken 1995.