ENVIRONMENTAL IMPACT OF EXHAUST EMISSIONS OF MARINE DIESEL ENGINES

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ABSTRACT

The naval field has entered the entangled picture of the fight against environmental pollution with some delay, because of the limited influence of sea traffic in comparison to other polluting sources. The aim of the present paper is to focus on the various aspects of pollution caused by marine engines, distinguishing them from those caused by road traction (according to the types of emissions, differences of application and "polluting capability" as regards urban areas), proposing those approaches to the problem that are nowadays possible, while considering the complexity and, first of all, the great variety of engines used in this sector.

PREFACE

The fleet at sea (i.e. all the ships nowadays at sea all over the world) is composed of different ships equipped with engines which can vary very much as regards their dimensions, functioning and, consequently, types of exhaust emissions. This should give a general view of the approach to the problem: if one wants to face the problem of the analysis, measurement, reduction and regularization of exhaust emissions, it is necessary to divide the fleet at sea adequately into categories, each of which requires a peculiar approach to investigation. However, it is clear that the method of facing the problem cannot leave aside any information coming from similar investigating activities in the field of road traction which, first among the internal combustion engines (ICE), has been called upon to normalize the emissions of such engines. Therefore, the know-how matured in this sector will unavoidably pass into the naval field, though the deep differences between the two types of applications need be considered carefully.
The methods defined for road traction engines will certainly confirm the evaluation of the polluting capability by means of the concept of "mission" i. e. of a sequence of possible runnings of the propulsion unit while at real operation: the correct choice of the mission for a given working unit means a good representation of the real working conditions.

MARINE ENGINES AND THEIR EMISSIONS

As said above, the whole of the main engines includes various types of engines differing from one another from the point of view both of manufacturing and working conditions. As regards the models nowadays at work, it is well-known that the greatest majority of the merchant vessels is equipped with ICE either two or four stroke engines. In particular, the diesel engines are classified as follows: low speed: generally 2-stroke, high stroke/bore ratio, up to 300 rpm; medium speed: generally 4-stroke, 300 to 1000 rpm; high speed: 4-stroke, over 1000 rpm. The engines of the first two classes are used in vessels with medium - high displacement, while high speed diesels are generally meant for smaller vessels or for generators on board.
All these engines have the typical characteristics of emissions of diesel engines: such characteristics are summarized in figure 1 indicating the flows of the various substances entering the engine (on the left)

and those emitted which are distinguished between those considered "physiological" (on the right) and the unwanted ones (in the bottom) [1].

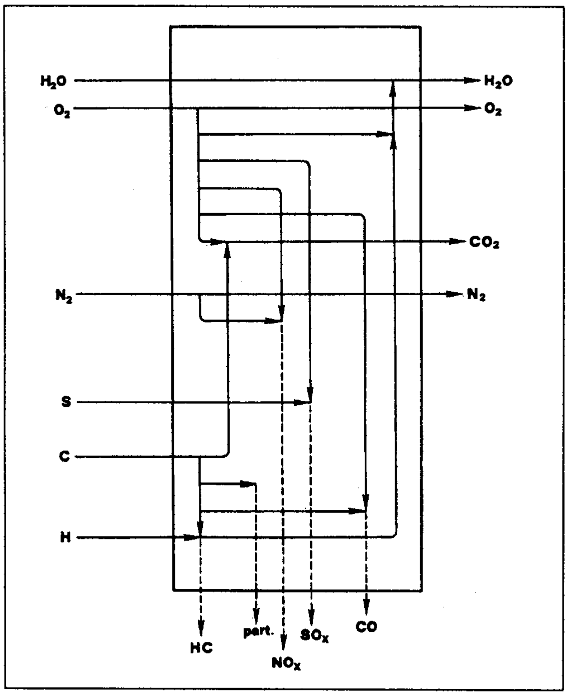

Fig. 1

A detailed picture of the main chemical substances of diesel exhaust is given in table 1 that shows the conditions of their forming together with their noxious effects on the environment.

TYPES OF VESSELS

In order to formulate correctly the mission profiles of each type of vessels, it is necessary to outline the categories within which vessels can be considered as homogeneous from the point of view both of the operating conditions and, consequently, of producing noxious substances. Three "classes" of vessels can be identified:

- medium and high tonnage cargoes, displacing, with a low or medium speed diesels, of medium-high power, medium - long routes, high ratio steady state/transient (long carriers, oil etc.)
- passenger ships ferries and cruise ships, displacing, with medium speed diesels (also diesel-electric), short or medium routes mostly close to the coast, frequent landing and medium to low ratio steady state/transient.

TABLE 1

CHEMICAL COMPOUND	SYMBOL	CONDITIONS OF FORMATION	NOXIOUS EFFECTS
Nitrogen oxides	NO_x	high temperature and high pressure combustion	harmful to the vegetation Californian smog acid rains
Sulphur dioxides	SO_x	sulphur in the fuel	respiratory system irritations
Carbon dioxide	CO_2	regular combustion product	greenhouse effect
Carbon monoxide	CO	defective combustion	destructive actions on hemoglobin
Total unburned hydrocarbons	THC	defective combustion	including aromatic hydrocarbons that are mutagen Californian smog
Particulate	PT	low combustion temperature and/or defective combustion	possibility of carrying THC and keeping them in contact with the respiratory system running the risk of activating their mutagen properties

- planing craft, with high or medium speed diesels delivering medium
- low power, short routes, very frequent landing, low or very low ratio steady state/transient (pleasure craft, fast ferries, patrol boats etc.).

Clearly some ships are left out from such a narrow schematization; however, we will refer to this classification to face the subject under question. The first class consists of ships that cover long routes, their presence next to urban areas is therefore limited to brief periods; but the situation becomes worse because of other attendant circumstances. First of all, the sizes of the engines are such as to cause the emission of large amount of exhaust gas and consequently, of large quantities of noxious substances; moreover, they are generally fed with low quality fuels, which obviously increases the amount of exhaust noxious substances. Once in the port, if not provided otherwise, the engines driving the alternator on board must be kept in operation (and under load) with the consequent no-stop emission of exhaust gas. Supposing that for this category of ships one would want to pursue the approach of reducing the emissions only near urban areas, there is nothing else to do but towing the ship into the port with the engine at the idle speed, fed with clean fuel and eventually keeping on the systems - if any - meant for lowering the noxious exhaust substances. For the means of the second class the situation is definitely more complicate because even if the size of the engine is still rather large, the periods of maneuvering, stop and go close to urban areas and to areas of landing (unavoidable in this case since towing into the port is impossible because of the necessity to curb the navigation period) are considerably increased. In such conditions the polluting risk arises and the intervention aiming at reducing the harmfulness of the emissions must be radical. Some favorable circumstances help lessening the effects of such situation like the curve of power delivery in "cubic" (and often with variable pitch propeller) which is less stressing on the engine, together with the use of fuels that are cleaner than those normally used in 2-stroke engines. The planing craft divide into a number of categories all of which are characterized by a power in "quadratic", unfavorable for the exhaust emissions. Pleasure craft, in great number but, generally, equipped with small engines and sailing almost always close to the coasts, does not have the assistance to navigation granted by a specialized crew as it happens for the larger size ships. This means it is necessary to adopt very reliable systems which can be managed by non-specialized personnel. Possible reductions in exhaust emissions must be obtained with systems always in operation and easy to maintain, as it happens with the new generation cars. The situation is less definite regards the high speed crafts (planing and semi-planing) for the transportation of passenger and goods (generally cars) next to the coasts; their working in quadratic makes it difficult to drop the emissions, which could be overcome with systems limiting the level either during the whole navigation or simply next to the urban areas. As regards the problem of the emissions as a function of the running condition of the hull, figure 2 shows in a qualitative way the theoretical towing power curve for a displacing vessel (curve 1) and for a planing one (curve 2) on an equal MCR.

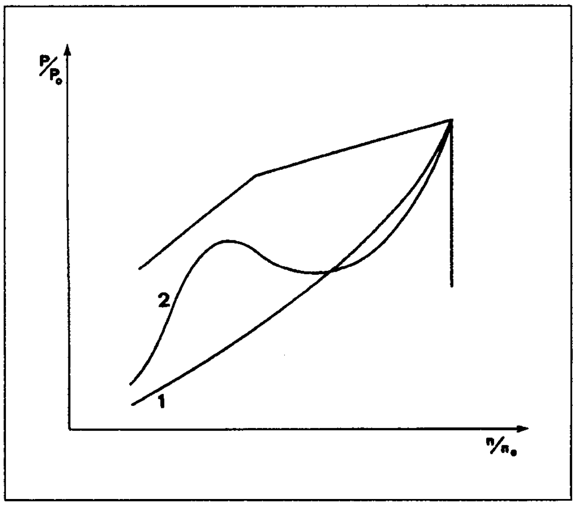

Fig. 2

The quantities are given in the percentage of their nominal value. The graphic shows as well the curves that must be considered as a limit for the normal running of the engine. It is easily understood that the planing conditions are more critical because the working points are closer to the limit curves. For each of the described categories, it is necessary to identify the most suitable mission profiles that is the one which, with the largest possible approximation, simulates the real working conditions of the engines. On the basis of mission profiles, as it happens in road traction, it will be possible to analyze the polluting behavior of naval engines and to know the most negative working conditions where to intervene to limit emissions. Normalization as well requires the definition of correct mission profiles in order to establish standards and limits to be imposed to naval engines similar to those already used in road traction (like the 13-mode method).

EXPERIMENTAL METHODS FOR LOWERING EMISSIONS

The study of pollution produced by diesels has shown that the substances to be reduced most urgently both for the quantity emitted and for their dangerousness are NO_x; among them particularly NO and NO_2 representing almost all the nitrogen oxides produced by diesel engines.
The order of magnitude of this phenomenon results to be as follows: a 4-stroke or 2-stroke diesel engine, fed with today's fuels, produces a quantity of NO_x of about 1000 - 1500 ppm where the maximum allowable limit is about 100 - 200 ppm [2] (it is impossible to give more precise values because there are no ultimate regulations indicating the maximum tolerable concentration of NO_x); this means, therefore, a remarkable quantity to be kept down and moreover, since nitrogen comes mostly from the intake air, it is not possible to knock down the flow in the combustion chamber and then reduce the quantity at the source.
It has been pointed out that the quantity of exhaust NO_x depends somehow on the injection timing, as the qualitative diagram in figure 3 shows.
This picture easily helps understanding that, with the increase of injection timing and therefore of the combustion time, there is a lessening of NO_x emission together with a rise of the fuel specific consumption. For a reduction of about 30-40% of NO_x the fuel consumption arises of about 5-6% because moving the injection phase from its optimal position from the point of view of the cycle worsens its efficiency.

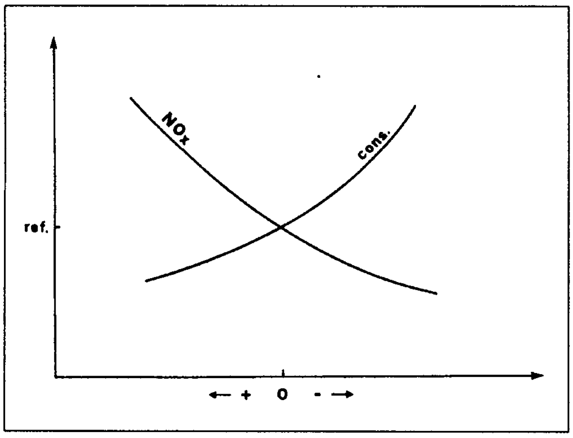

Fig. 3

It is possible to lower the NO_x production also by adding water into the fuel (at the rate of 15 to 25 % [3]).
This causes a better atomization of the fuel injected into the cylinder (since the flash of the water increases the "dispersion" effect of the flow already obtained by means of an appropriate injection pressure) while lowering the combustion temperature which, as said before, reduces the emission of NO_x.
The disadvantage of such a solution consists mainly in the fact that the engine, in order to burn hydrated fuels, must be adapted to such aim, the injectors must be protected from the corrosive action of the steam, it is necessary to prevent the water from infiltrating into the lubricant and polluting it etc. Moreover, this way does not reduce NO_x remarkably, while, on the other hand, it requires the engine to be equipped so as to work with hydrated fuels.
It is difficult to imagine a plant capable of working both with normal and hydrated fuels. The most incisive method (not lacking, unfortunately, complications and difficulties) of reducing the concentration of exhaust NO_x in high-power diesels is the SCR (Selective Catalytic Reduction) system [2].
In such a systems the gases coming out of the cylinders are introduced into a reactor where the ammonia cycle changes the NO_x into biatomic nitrogen and water by means of the following reactions:

$$4\ NO + 4\ NH_3 + O_2 = 4\ N_2 + 6\ H_2O$$

$$6\ NO_2 + 8\ NH_3 = 7\ N_2 + 12\ H_2O$$

Such a system can be active either continuously or when the concentration of NO_x overcomes the fixed maximum values; in order to have it work in the second way an instantaneous measurement of the NO_x emissions should be supplied which should be capable to intervene either by signaling that the production of NO_x exceeds the accepted limit or by activating the SCR reactor directly.
Of course, the amount of exhaust NO_x depends on various factors, such as the engine load, its speed, the temperature and the flow of the scavenging air etc. Since during the engine operation it is necessary to adjust the flow of NH_3 to the quantity of the NO_x to be neutralized, the plant must be supplied with an electronic device which adjusts the flow of NH_3 to be introduced into the reactor as a function of some input parameters.
Figures 4a, 4b, 4c show the layout of an experimental plant installed on board of a ship.
What we have just said is very far from lacking problems and some real disadvantages from the point of view both of its manufacturing and working; first of all, the manufacturing difficulties are evident

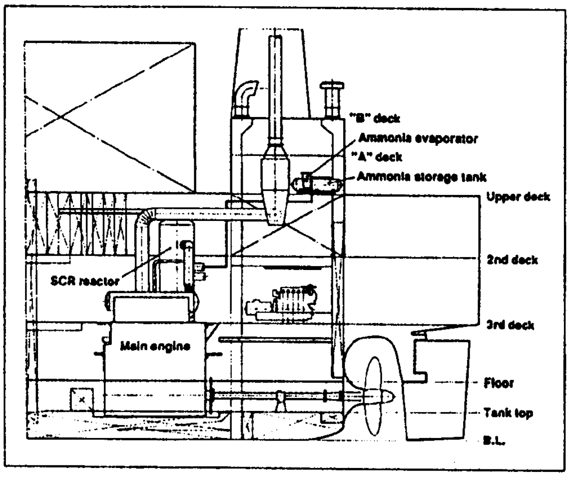

Fig. 4a

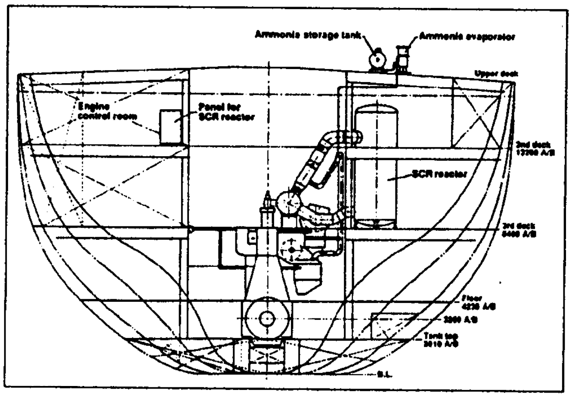

Fig. 4b

especially for those engines, as the current ones, where the room among elements is extremely reduced. The ammonia cycle makes the plant and the safety problems more complicate besides requiring a very strict check of the possible presence of exhaust NH_3 which could be even more dangerous than the presence of NO_x since ammonia is a very active gas; its combination with SO_3 in the cooling exchanger can create a generation of ammonia sulphurs which clogs the pipes.
Moreover, the working of such a plant causes a cost equivalent to a rise in specific consumption around 10 g/kWh which rises even more if it ads to the costs of installing, maintenance and capital [4]; this means sums which would be very difficult to propose to the shipowners traditionally sensitive to reductions in specific consumption and for whom the rising even of 1 g/kWh already means a discriminating factor. But together with such negative implications, we can as well consider the fact that the SCR reactor can lower, at any work conditions, the rate of exhaust NO_x from 1600 to no more than 130 ppm.
The lowering of SO_x has reached further importance with the adoption of heavy fuels which, since containing a large quantity of sulphur, are responsible for the rising of SO_3 which can cause the production of sulfuric acid. The presence of sulphur into the combustion chamber, moreover, catalyzes the formation of the particulate.
The method traditionally used to lower the production of sulphur compounds is the balancing of the TBN of the oil for the separate lubrication (in 2-stroke engines) to fight the acidity in the

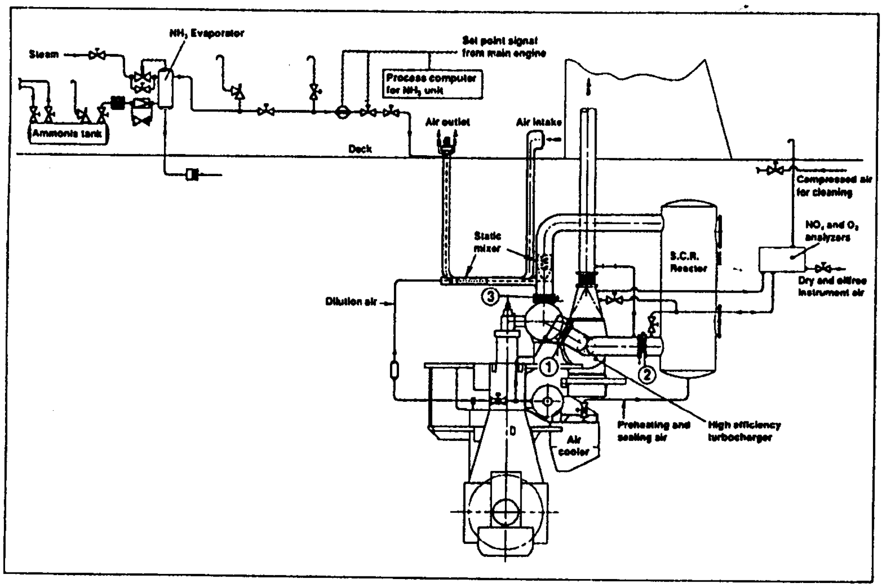

Fig. 4c

combustion chamber and consequently the forming of sulfuric acid; however the best way seems to be lowering the rate of sulphur in the fuel which can be reached with today's technologies but increases the price of the product.

A number of methods to remove CO, CO_2, PT ant THC are under study at the moment, even if the attention is mainly focused on lowering the NO_x.

As for the CO, which creates only minor problems (mostly in dual-fuel engines) it can be oxidated into CO_2 by post-burners. As regards the particulate, the best way seems to be the fluidized bed catalyst which, like SCR, requires large plants and, thence, creates similar problems to those described in catalyzing the ammonia cycle (though free of problems derived from the chemical aggressiveness of the NH_3). Recently, a new device has been created which, once applied to the exhaust pipe should lower the particulate: it consists in a filter which can be regenerated, containing a ceramic core [5,6]. Because of its porosity, it can trap the solid particles of burned gases passing trough it.

The first applications, although interesting on a theoretical level, have already shown great problems due to the use of such devices: the clogging takes place after few operational hours (about 8÷10 for 300 kW engines).

The regeneration performed up to now requires the use of high-temperature burners that clear the filter by burning the clogging particulate. Therefore each plant should at least be supplied with two filters, one working and the other, in stand-by condition after the regeneration, will start working when the first gets clogged.

The dimensions of such a plant are, for the moment, too large for the marine application, while the method of regeneration now in use seems to be still too dangerous because of the high temperatures involved and for the presence of a free flame heater.

HYPOTHESIS OF AN EXPERIMENTAL INVESTIGATION

As said before, the strong differences existing in the naval field prevent a common approach to the problem and require setting up different methods on measurement, analysis and limiting of their emissions. It is, therefore, evident that the more the engine size grows, the more the investigation becomes difficult because of the complications in the experimental survey and in dimensioning the required equipment. On limiting, for the moment, the investigation to medium-to-small size engines, a complete enquiry of the phenomenon of pollution should consider at least its two main effects: the influence on the air and water quality, both aspects reducing the life-quality of the environment close to the coasts where mainly small engine vessels circulate. From the point of view of air pollution, a possible way seems to be an overall transfer of the technology matured up to now in the field of road traction engines into the naval one.

To justify such a choice we can point out not only the conveniency of the use of already tested technologies (although in the other fields) but also the extreme easiness in operating because of the great similarity of small-size marine and road engines; so measurement, analysis of contents and experimental investigation of exhaust gases can be carried out with the same instruments already existing in the laboratories engaged in the research on road engines.

As regards rules limiting the emissions, it is necessary to determine, as it happened in road traction, mission profiles and calculation methods of standard values appropriate for marine applications. Such values must then be compared to the maximum tolerable values of exhaust noxious chemical substances which will be considered as appropriate to the preservation of the environment where the vessels equipped with such engines are going to work.

This is what is already happening all over the world: the engine manufacturers are already engaged in determining mission profiles including the weight factor for each working phase, which should simulate plausibly the real operating conditions of the engine under investigation (although sometimes, to tell the truth, they seem to reflect upon the wish to make one's own engine work in given times and fields when the emissions are particularly limited rather than anything else).

Table 2 shows some cycles with the related weight factors proposed in some experimental situations, among which the ISO 8178 regulation, recently modified [19].

Such cycles are compared with the common "father" of all mission profiles, that is the "13-modes cycle" nowadays well-affirmed in tests on emissions of road traction.

It is likely that the establishment of one or more cycles well reflecting upon the operating conditions where various models of vessels interested in such problems will work, will create the basis for a future agreement in the appropriate committees for the normalization of emissions in the naval field.

The problem is not simpler on the "water side": it is well known that most small vessels are equipped with an exhaust system mixing gases emitted by the engine with sea water so as to cool their content.

TABLE 2

13 MODES(*)				PROJECT ISO 8178										PROJECT A - CH - D (5)			
				E_1 (1)	E_2 (2)	E_3 (3)				E_4 (4)							
	V	P	WF	WF	WF		V	P	WF		V	P	WF		V	P	WF
1	M	0	0.25/3	5 0.40													
2	I	10	0.08	- -													
3	I	25	0.08	4 0.25													
4	I	50	0.08	3 0.15													
5	I	75	0.08	2 0.14													
6	I	100	0.25	- -													
7	M	0	0.25/3	- -										9	$n(P_{max})$	P_{max}	0.05
8	R	100	0.10	1 0.06	1 0.20	1	100	100	0.20	1	100	100	0.06	8	n(nom)	P_{nom}	0.05
9	R	75	0.02	- -	2 0.50	2	91	75	0.50	2	80	71.6	0.14	7	0.9 nom	0.7884 P_{nom}	0.05
10	R	50	0.02	- -	3 0.15	3	80	50	0.15	3	60	46.5	0.15	6	0.8 nom	0.5724 P_{nom}	0.05
11	R	25	0.02	- -	4 0.15	4	63	25	0.15	4	40	25.3	0.25	5	0.7 nom	0.4100 P_{nom}	0.2
12	R	10	0.02	- -	- -	-	-	-	-	-	-	-	-	4	0.6 nom	0.2789 P_{nom}	0.1
13	M	0	0.25/3	- -	- -	-	-	-	-	5	0	0	0.40	3	0.5 nom	0.1768 P_{nom}	0.1
														2	0.4 nom	0.1012 P_{nom}	0.1
														1	idle	0	0.3

(*) ECE/ONU r.49 Dir. 88/77/CEC for diesel engines for cat. M2, M3, N2, N3 vehicles
Agreement AUSTRIA-SWITZERLAND-GERMANY for P_{max} > 100 kW (The power is percentage of maximal power)

(1) "PLEASURE CRAFTS": for diesel engines only } speed and power are the same as for

(2) "HEAVY DUTY CONSTANT SPEED ENGINES FOR SHIP PROPULSION" } the "13 modes" (on the same line)

(3) "HEAVY DUTY MARINE ENGINES"

(4) "PLEASURE CRAFTS": for gasoline engines only

(5) P_{max} < 100 kW

LEGENDA: V = speed; P = power; WF = weight factor; M = idle; I = intermediate; R = rated

Two effects are caused by such an exhaust system:

- one part of the exhaust is dissolved in the water polluting it;
- another part, first introduced in the water by the exhaust s ystem, releases it self afterwards so contributing to the pollution of the air around the vessel.

Both such effects must be limited. It is understood in fact that the well-known problems rising along the seaside and next to urban areas in general because of the air pollution due to the simultaneous presence of many ships (enhancing the effect of overall pollution) adds up to the sea-fouling caused by discharging of even small quantities of noxious substances into the water. Such phenomena, distinct but parallel, can be studied by a laboratory research on systems equipped with sea-water cooling aimed at establishing the average percentage values of emissions which are directly delivered into the air, and those delivered into water which stay there and finally that part of the emitted substances which, first dissolved in the water, releases itself contributing mainly to air pollution. The start of such an investigation is going to be organized through a cooperation between the CNR Istituto Motori of Naples and the Dept of Naval Engineering of the "Federico II" University of Naples. Such an investigation can be carried out by installing a dynamometric brake next to a tank suitably proportioned and capable of receiving the waters coming from the cooling system of the exhaust of the engine tested at the bench. So it would be possible, by means of the traditional instruments, to measure the share of emissions which are delivered into the air, and through the chemical analysis of the water in the tank moreover it should be possible to define the quantity of exhaust remained in the water. Time tests of stability will, on the other hand, permit to establish the gaseous amount which, once introduced in the water, stays there and the one (by difference or by direct measurement) releases itself afterwards.

CONCLUSIONS

The normalization of emissions of naval engines today faces the following difficulties:

- non-uniform types of vessels which require different approaches to each category of ships;
- double front of environmental pollution: air and water;
- varying characteristics of fuels used in marine engines;
- need to identify methods for checking the circulating fleet.

Today the ISO 8178 project is asserting itself; it includes various field of propulsion also for marine use. The acceptance of this by each national association will require an investigation of the mechanisms of emission and a definition of the testing systems (under test bed conditions and at site) of emissions from the marine exhaust systems. Moreover the research in the sector will give information about the emission characteristics of large size engines (also in transient conditions) so as to limit them. This will be reached by some "philosophies" of the use of the potentially pollutant sources. In other words, it will be necessary to settle "how much" and "where" we can pollute being aware that the modern industrial systems (and not only those connected to the naval field) must consider as a target, among other things, an increasing limitation of the pollutant emissions

BIBLIOGRAPHY

[1] Landri, G.; Paciolla, A.; Polletta, A.; Quaranta, F.: The problem of exhaust emissions of marine diesel engine; NAV 92 Congress, Genoa 7 - 10/7 1992

[2] Grøne, Ö.: Emission control of large diesel engines; Motor Ship XIII Conference, London 3/91

[3] Tayama, K.: The environmentally-frendly marine engine; Motor Ship XIII Conference, London 3/91

[4] Paro, D.: Propulsion systems in harmony with the environment; Motor Ship XIII Conference, London 3/91

[5] Balzotti, A.; Cornetti, G.; Pidello, F.; Scorsone, V.: Convenzione tra Ministero dei Trasporti, ATAC Roma ed Iveco per la sperimentazione di un sistema per l'abbattimento della fumosità dei gas di scarico dei motori diesel; Ministero di Trasporti, Roma, 1990

[6] Balzotti, A.; Cornetti, G.; Pidello, F.; Signer, M.; Scorsone, V.: Italian city buses with particulates traps; SAE Technical Paper 900114; presented at the International Congress and Exposition of Detroit (Michigan), 26-2/2-3 1990

[7] Reynolds, G.: Marine diesel engine exhaust emissions during steady state and transient operation; Motor Ship XIII Conference, London 3/91

[8] Lloyd Register of Shipping: Marine exhaust emission research programme; Motor Ship XIII Conference, London 3/91

[9] Kimstra, K.: The mechanics of NO_x formation and in-engine measures to reduce NO_x emission; some development results; Motor Ship XIII Conference, London 3/91

[10] Alexandersson, A.: Exhaust emission from sea transportation; Motor Ship XIII Conference, London 3/91

[11] Bastenhof, D.:
Environmental aspects in medium-speed four-stroke diesel engines;
Motor Ship XIII Conference, London 3/91

[12] Veenstra, G.:
Low NOx emissions with TM 620;
Stork-Wärtsilä diesel revue n° 49, 90

[13] Sukoh,S.; Hokary, Y.:
Experimental investigation on characteristics and reducing of NOx emission of marine two stroke diesel engine;
CIMAC XIX Congress, Florence 91

[14] Sondeergaard, K.; Morsing, P.:
NO_x control for large marine diesel;
CIMAC XIX Congress, Florence 91

[15] Holbrok, P.; Pogonowska-Fabriek, W.:
Diesel engine operation and the environment;
CIMAC XIX Congress, Florence 91

[16] Hullsmann, B.; Havenith, C.:
Influence of high density fuels combustion and emission behaviour of marine diesel engine;
CIMAC XIX Congress, Florence 91

[17] Gros, S.:
Environmental control of marine installations;
Wärtsilä Group Marine News, n° 1/1991

[18] Pallin, M. D.:
The future of regulation and control of exhaust emissions during steady state e transient operations;
1990 Ship Operations, Management and Economics Symposium USMMA, Kings Point, NY, April 1990

[19] INTERNATIONAL ORGANIZATION FOR STANDARDIZATION: ISO/TC70/SC8 RIC eng. exhaust emissions measurement; ISO 8178 exhaust measurement procedures for non road engines, doc n°49, rev 1992/04/06; ISO 8178, part 4 test cycles for different engine applications, doc n°85, rev 1992/03/19

[20] GU - REPUBBLICA ITALIANA SO n°229 30/09/1989 (serie generale) DM 5/6/89 - limiti alle emissioni di gas inquinanti prodotti da motori ad accensione spontanea destinati alla propulsione di veicoli - (Dir. 88/77/CEE, 31/12/1987)

[21] GU - REPUBBLICA ITALIANA SO n°77 1/04/1992 (serie generale) DM 23/3/92 - nuovi limiti alle emissioni di gas inquinanti prodotti da motori ad accensione spontanea destinati alla propulsione di veicoli - (Dir. di modifica 91/542/CEE, 1/10/1991 alla 88/77/CEE)