Development of marine engines for fulfilling IMO emission regulations for yachts

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Abstract

Several different solutions have been considered worldwide for reducing exhaust emissions, such as applying alternative fuels and developing high efficiency engines. IMO societies have laid down guidelines for future limits on emission contents, taking into consideration different applications and exploitation of marine engines. Engine manufacturers have been forced to develop new technologies to fulfil the existing and future IMO emission regulations. The paper analyses some of the new methods and technologies of highly efficient engines meeting new regulations.
Keywords: marine engine, IMO regulations, exhaust emission.

1 IMO regulations for reducing emissions from ship exhausts

1.1 IMO (International Maritime Organization)

Environmental pollution is, to a large extent, affected by shipping industry, i.e. vessels as means of sea transport. Therefore, there is a great need for international standards regulating maritime treaties and applying to all countries. The first international convention of this kind was SOLAS, adopted in 1914 following the Titanic disaster. SOLAS stands for Safety Of Life At Sea and the convention explicitly referred to rescuing people at sea. The International Maritime Organization (IMO), formerly known as the Inter-Governmental Maritime Consultative Organization (IMCO), was established in Geneva in 1948, and entered into force ten years later, meeting for the first time in 1959. The IMO's main task has been to develop and maintain an overall regulatory framework for shipping and its remit today includes safety, environmental issues, legal matters, technical cooperation, maritime security and the efficiency

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Table 1: Allowed limits of exhaust emissions according to the suggested EPA Tier 3 for Category 1.

Power coefficient	Volume (*L/cyl*)	Maximum rated output	Model, Year	Particulate matter (*g/kWh*)	NOx + HC (*g/kWh*)
All	Vol. < 0.9	kW < 19	2009	0.4	7.5
		19 ≤ kW < 75	2009	0.3	7.5
			2014	0.3	4.7
Commercial engines kW/L ≤ 35	Vol. < 0.9	kW ≥ 75	2012	0.14	5.4
	0.9 ≤ Vol. < 1.2	Svi	2013	0.12	5.4
	1.2 ≤ Vol. < 2.5	kW < 600	2014	0.11	5.6
		600 ≤ kW ≤ 3700	2018	0.10	5.6
	2.5 ≤ Vol. < 3.5	kW < 600	2013	0.11	5.6
			2018	0.10	5.6
		600 ≤ kW ≤ 3700	2013	0.11	5.6
	3.5 ≤ Vol. < 7.0	kW < 600	2012	0.11	5.8
			2018	0.10	5.8
		600 ≤ kW ≤ 3700	2012	0.11	5.8
Commercial engines kW/L > 35 and all recreational engines	Vol. < 0.9	kW ≥ 75	2012	0.15	5.8
	0.9 ≤ Vol. < 1.2	kW ≥ 75	2013	0.14	5.8
	1.2 ≤ Vol. < 2.5	kW ≥ 75	2014	0.12	5.8
	2.5 ≤ Vol. < 3.5	kW ≥ 75	2013	0.12	5.8
	3.5 ≤ Vol. < 7.0	kW ≥ 75	2012	0.12	5.4

of shipping. The Marine Environment Protection Committee (MEPC) of the International Maritime Organization directly deals with prevention of air pollution from ships. The most important convention initiated by the IMO, i.e. the MEPC, is the International Convention on the Prevention of Pollution from Ships (MARPOL) which was adopted in 1973 and amended in 1978 when it entered into force as MARPOL 73/78. In addition to oil pollution, the convention addresses exhaust pollution and pollution caused by chemicals, packed goods, waste waters and dumping.

1.2 Maritime regulations on reduction of exhausts in compliance with the EU and EPA

Apart from IMO conventions, the existing and future maritime regulations on reduction of exhausts have been incorporated in the documents of other maritime organisations such as the US Environment Protection Agency (EPA) or the documents of the European Union (EU). Thus the following conventions have come into force: 1) IMO Tier 1 and Tier II; 2) EPA Tier 2 (commercial and recreational craft); 3) EU (Waterways 97/68/EC, amended by 2004/26/EC; Guidelines for commercial craft 94/25/EC, amended by 2003/44/EC; CCNR I & II; 4) Suggestions EPA Tier 3 and Tier 4; 5) 3CARB.

1.2.1 EPA (Exhaust emission limits set by EPA)

The US agency EPA has also set future regulations on exhausts, which have been included in the suggested EPA Tier 3, applying to vessels in the Category 1, as shown in Table 1.

The EPA Tier 3 lays down regulations for larger marine engines as well (Category 2), installed on either commercial or recreational craft. The values are shown in Table 2.

Table 2: Allowed limits of exhaust emissions according to the suggested EPA Tier 3 for Category 2.

Volume (*L/cyl*)	Maximum rated output	Model, Year	Particulate matter (*g/kWh*)	NOx + HC (*g/kWh*)
7.0 ≤ Vol. < 15.0	kW ≤ 3700	2013	0.14	6.2
15.0 ≤ Vol. < 20.0	kW ≤ 3300	2014	0.34	7.0
	3300 < kW ≤ 3700	2014	0.27	8.7
20.0 ≤ Vol. < 25.0	kW ≤ 3700	2014	0.27	9.8
25.0 ≤ Vol. < 30.0	kW ≤ 3700	2014	0.27	11.0

In addition to Tier 3, Tier 4 refers to the engines in Categories 1 and 2, specifying the emission values as shown in Table 3.

Table 3: Allowed limits of exhaust emissions according to the suggested EPA Tier 4 for Categories 1 i 2.

Application	Maximum rated output	Volume (*L/cyl*)	Model, Year	Particulate matter (*g/kWh*)	NOx (*g/kWh*)	HC (*g/kWh*)
Commercial	600 ≤ kW < 1400	All	2017	0.04	1.8	0.19
Commercial	1400 ≤ kW ≤ 2000	All	2016	0.04	1.8	0.19
Commercial and recreational	2000 < kW ≤ 3700	All	2016	0.04	1.8	0.19
Commercial and recreational	kW > 3700	Vol. < 15.0	2014	0.12	1.8	0.19
		15.0 ≤ Vol. < 30.0	2014	0.25		
		All	2016	0.06		

Commercial versus recreational craft as classified according to EPA: 1) Recreational craft is a craft which has been built or used with the purpose of leisure; 2) Commercial engines can be used in recreational craft but recreational engines can not be used in commercial craft; 3) Passenger craft and small passenger craft must be considered separately from recreational craft. These passenger craft must use commercial engines (Small passenger craft are less than 100 GT and may transport 6 or more passengers; Passenger craft are larger than 100 GT and may transport one or more passengers; The captain and the crew are not considered as passengers).

1.2.2 EU maritime regulations on exhaust emission

The limits of exhaust emissions from the ships sailing under the EU flags are set in the maritime regulations 94/25/EC for recreational craft. These limits' values are shown in Tables 4 and 5.

Table 4: Allowed limits of exhaust emissions according to EU regulations 97/68/EC for commercial craft.

Category: Swept volume/net output RO/P – litres per cylinder/kW	Entered into force since	CO (*g/kWh*)	HC + NOx (*g/kWh*)	Particulate matter (*g/kWh*)
V 1:1 RO < 0.9 P >= 37 kW	31 Dec 2006	5.0	7.5	0.4
V 1:2 0.9 <= RO < 1.2	31 Dec 2006	5.0	7.2	0.3
V 1:3 1.2 <= RO < 2.5	31 Dec 2006	5.0	7.2	0.2
V 1:4 2.5 <= RO < 5.0	31 Dec 2008	5.0	7.2	0.2
V 2:1 5.0 <= RO < 15.0	31 Dec 2008	5.0	7.8	0.27
V 2:2 15.0 <= RO < 20.0 P <= 3300 kW	31 Dec 2008	5.0	8.7	0.50
V 2:3 15.0 <= RO < 20.0 P > 3300 kW	31 Dec 2008	5.0	9.8	0.50
V 2:4 20.0 <= RO < 25.0	31 Dec 2008	5.0	9.8	0.50
V 2:5 25.0 <= RO < 30.0	31 Dec 2008	5.0	11.0	0.50

Table 5: Allowed limits of exhaust emissions according to EU regulations 94/25/EC for recreational craft.

Engine type	CO (g/kWh)	HC (g/kWh)	NOx (g/kWh)	Particulate matter (g/kWh)
Compression ignition Applicable as from 31 Dec 2005	5.0	$1.5 + 2.0 / (Pn)^{0.5}$	9.8	1.0

2 Development and application of new technologies for fulfilling IMO requirements

Different solutions have been considered worldwide for reducing exhaust emission, such as applying alternative fuels and developing high efficiency engines. IMO societies have laid down guidelines for future limits on emission contents, taking into consideration different applications and exploitation conditions of marine engines. Engine manufacturers have been forced to develop new technologies to fulfil the existing and future IMO emission regulations.

2.1 ACERT technology of the CATERPILLAR four-stroke engines

The ACERT (Advance Combustion Emission Reduction Technology), as one of the best and most comprehensive technologies aimed at reducing harmful emissions of air pollutants from vessels, represents one of the solutions to the existing and future IMO regulations on exhaust emissions described in paragraph 1 (Hind [1], [2]). As the exhaust criteria become tighter, ACERT technology does not lag behind. Unlike other solutions, ACERT offers clear directions for compliance with future regulations. The technology is entirely based on precise electronic control of engine operation achieving complete and precise combustion of fuel and, consequently, resulting in a high efficient engine with minimum exhaust emissions. The end result is an engine that exceeds emissions requirements quietly and with less smoke. What makes ACERT technology good for the environment also makes ACERT good for engine performance. Efficient combustion reduces engine wear and maximizes the amount of fuel energy applied to the propeller or generator. Instead of incomplete combustion creating black smoke that is seen passing through the exhaust, the technology drives the combustion system to pull the maximum amount of energy from each injection. As ACERT is primarily a combustion technology, there is no external plumbing to clutter cramped engine rooms. When specifying an engine, ACERT technology building block components are included only as needed, so that it is possible to get a solution which is customized and optimized for a specific application. The technology removes complications and costs of the system for reducing toxic elements by injecting an emulsion during expansion and the costs of the chemical catalyst system. The building block components can be added as needed and constantly upgraded in order to improve efficiency. There are four categories of building blocks: fuel delivery, electronics, air management, combustion management.

2.1.1 Fuel delivery

One of the key breakthroughs in ACERT technology has been the development of fuel delivery into the combustion chamber through multiple injections. The multiple-injection process introduces fuel into the combustion chamber in a number of precisely-controlled microbursts. Injecting fuel in this way allows for precise shaping of the combustion cycle. A Cat ADEM 4 controller is an electronic unit which directs either HEUI (Hydraulically Actuated Electronically Controlled) unit injector system or MEUI (Mechanically Actuated Electronically Controlled) unit injector system to deliver precise quantities of fuel at exactly the right time during combustion. These proprietary Cat injectors can deliver the control and pressure needed for complete combustion. Hence, by introducing ACERT building block components for fuel delivery control, the following is achieved: 1) Delivery of fuel into the combustion chamber in a number of precisely-controlled microbursts; 2) Optimum performance, i.e. maximum output and efficiency with minimum emissions at a wide range of engine rating and load.

2.1.2 Electronics

The “brain power” for ACERT technology comes from Cat ADEM 4 electronic controllers that are installed in the very engine block. These electronic controllers coordinate and enhance the engine’s functions, improving the overall engine performance and reducing harmful emissions from exhausts. The unit can be programmed to optimize performance for different engines or specific applications.

2.1.3 Air management

Advanced air management in marine engines also plays a critical role in reducing emissions. The construction features of the air management system, developed for enhancing engine performance, include: crossflow cylinder heads, turbochargers, updated valve train components, serial turbocharging, Flex Cam technology developed by the marine engines manufacturer MAK from Kiel.

2.1.4 Combustion management

The research has been focused on the controlled combustion, including: 1) Optimising the new flexible systems; 2) Use of advanced modelling software for selecting the optimum nozzle configuration and cylinder geometry.

2.2 MAN B&W new technologies for reducing exhaust emissions from marine slow-speed two-stroke engines

Increasing requirements for the reduction of the exhaust emissions have been encouraging the marine engine manufacturers to search for new technologies. The latter have been developed by all leading marine engine manufacturers with the purpose of meeting new standards introducing the limitations on exhaust emissions. MAN B&W has introduced new slide-type fuel valves (injectors) as a standard feature of every new engine (Henningsen [3, 4]). The application of these valves has proven considerable fuel consumption saving, cleanliness of engines, and reduction of exhaust emissions. In addition to slide valves, MAN has been developing and applying secondary methods of exhaust emissions reduction, such as using water-in-fuel emulsions and selective catalytic reduction, aiming to achieve better results in emissions reduction.

2.2.1 Slide valve (injector) MAN B&W

In order to reduce harmful emissions from their slow-speed engines, MAN B&W has launched a new slide-type valve for fuel injection. This valve type has minimised the risk of subsequent penetration of fuel into the combustion chamber after the fuel injection. This directly results in reduction of emissions of carbon monoxide (CO) and volatile organic compounds (VOC) as, in the engines featuring this type of valve, there is no incomplete combustion as a result of fuel entering the cylinder after the combustion process has been completed. In addition to the development of slide-type fuel valves, MAN B&W has also optimised the nozzle for achieving lower NOx emissions. Compared to conventional fuel valves and nozzles, in this way a 25% NOx reduction at 90% engine load has been achieved, with an increase in fuel consumption of only 1%. Likewise, these engines have a reduced smoke emission. Slide valves fitted to MAN marine engines ensure optimised combustion and cleaner engines. Enhanced combustion decreases the amount of non-burnt hydrocarbons (around 30%) and particulate matter, which results in less smoke. Furthermore, the piston top ends suffer less load and wear, as is the case with the exhaust gas boilers, resulting in minimum wear of the exhaust valve seats. Most importantly, the slide valve, i.e. the fuel valve nozzle, entirely complies with the IMO requirements on NOx emissions reduction.

2.2.2 Emulsion of water and fuel

In order to fulfil the requirements on emissions reduction and enhance the results achieved by using slide valves, MAN has integrated the water-in-fuel emulsion technology into their marine engines. Adding water to fuel considerably reduces NOx emissions. A standard engine allows emulsions of fuel with 20% of added water at full load, although even 50-50% water-fuel emulsions have been tested.

The results of emulsified fuels may vary, depending on the engine type, but basically one percent of water reduces the NOx emission by approximately one percent. In engines using heavy diesel oils it is possible to apply a pure emulsion of water and fuel, whereas in gasoline engines it is possible to use the emulsion only after introducing an emulsifying agent. Typical agents for this application are cheap plant proteins which are used as industrial food for cattle. The control of the amount of water added to fuel can be carried out with regard to the fuel flow or the amount of NOx released at the exhaust. Vessels using emulsified fuels are fitted with a specially designed safety system. In the event of power breakdown, such a system ensures stable and uninterrupted blending of water and fuel as well as engine start-up without switching to fuel without water.

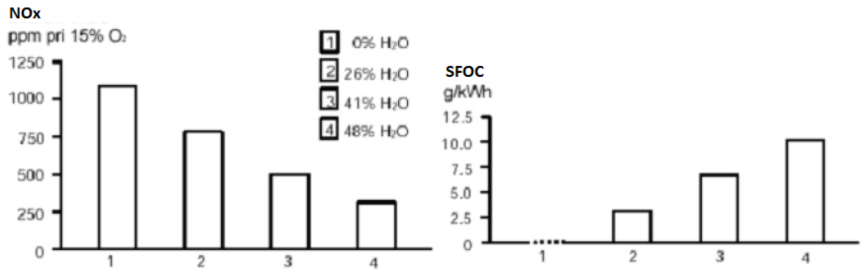

Figure 1: Impact of fuel-water emulsion on NOx emission and specific fuel consumption (SFOC).

2.2.3 Selective catalytic reduction (SCR)

The selective catalytic reduction (SCR) process reduces NOx emissions to harmless ingredients which are normally contained by the air we breathe. The SCR is currently the most efficient technique for decreasing the NOx emissions that are reduced in this way by 85-95%. The means of reduction (urea) is injected into exhaust gases at a temperature between 290 and 450°C. The reduction of NOx emission will depend on the amount of the injected urea but it can also be achieved by increasing the catalyst volume. If there is an exhaust gas boiler on board ship, it has to be placed behind the SCR as the SCR technique requires relatively high operating temperatures.

2.2.4 Biodiesel

Criteria on exhaust emissions reduction are becoming increasingly tighter, requiring new technologies and solutions aimed at meeting future regulations and standards which are to be set with the purpose of reducing exhaust emissions and preserving environment. One of the solutions is the application of alternative fuels such as biodiesel. Biodiesel is an alternative renewable fuel which is, in energy policy acts, defined as “fuel for engine vehicles manufactured from vegetable oils, animal fats, or recycled greases, as an alternative to fossil fuels. Renewable fuels include bioethanol, biodiesel, and other fuels for engine vehicles, which are extracted from renewable sources. From the chemical point of view, biodiesel is a methylated-ether fat acid manufactured from vegetable oils and animal fats. In marine diesel engines, biodiesel can be used in various percentages, with a few minor engine conversions. Various types of biodiesel fuels require respective designations so that each separate type can be designated according to its basic specification. The basic nomenclature of biodiesels is as follows: 1) B05 = 5% biodiesel + 95% oil diesel; 2) B20 = 20% biodiesel + 80% oil diesel; 3) B100 = 100% biodiesel. Table 6 shows the values referring to exhaust emissions reduction when burning biodiesel if compared to the exhaust emissions of oil diesel.

Table 6: Average change in exhaust emissions as compared to diesel oil.

Emissions	B100	B20	B2
Non-burnt hydrocarbons	-67%	-20%	-2.2%
Carbon monoxide	-48%	-12%	-1.3%
Particulate matter	-47%	-12%	-1.3%
Nitrogen oxides (NOx)	+10%	+2%	+.2%

Moreover, biodiesel fuels tightly comply with the requirements regarding the reduction of sulphur emissions into the atmosphere. The advantages of biodiesels include: 1) Environment: emissions reduction, 78% reduction of the CO_2 life cycle; 2) Energy safety and independence: biodiesels reduce the need for importation of energy and improve the balance in energy trade; 3) Economy: biodiesel manufacturing creates jobs, generates revenues, and opens a wider market for agriculture; 4) Higher cetane rating (on average higher than 50); 5) Very low sulphur content (on average ~ 2 ppm); 6)High lubricity rating, even in blends of 1-2%; 7) Biodiesels reduce the percentage of hydrocarbon CHx emissions, particulate matter (PM) and carbon monoxide CO in exhaust gases; 8) High energetic ratio (from 3.2 to 1); 9) Little agriculture investment – soya seeds; 10) Renewable and sustainable, domestic produce of any country; 11) Machinery and engine friendly: B20 has 66% better lubricity rating than pure petroleum-based diesel fuel, which improves engine efficiency and operating life cycle; 12) Since mid-2006 biodiesel have been meeting EPA standards on exhaust emissions. Disadvantages of biodiesel: 1) The greatest disadvantage of biodiesel is poor quality; 2) Reduced fluidity at low temperatures; 3) Filtered residuals from fuel: glycerine, may draw old fuel deposits due to reduced fluidity; 4) Damages to injector needle in case of larger deposits of impurities; 5) Lower fuel economy and engine power (8-10% lower for B100, minimum reduction of power for B20); 6) May contain water, hence requires water separator; 7) Lower stability of fuel: it is subject to oxidation, biodegradation and microbial development; 8) Can not be stored for a long time: B20 maximum 6 months, B100 maximum 1 month in a tank; 9) Compatibility with other materials: most metals (brass, bronze, copper, lead, tin and zinc) may foster the oxidation of biodiesel fuels. Fuel tanks made of lower quality steel may corrode due to water content in the fuel. Corrosion can be prevented by using tanks made of stainless steel or plastics; 10) Dilution of engine oil by biodiesel fuel: rich blends may result in fuel dilution. It is necessary to control the oil quality: biodiesel may decrease intervals between oil exchange from the engine crankcase; 11) Higher price.

3 Conclusion

IMO requirements and other regulations on the reduction of emissions exhaust and environment protection are becoming increasingly tighter and the allowed limits are getting lower. The trend is to completely eliminate pollutants. The world's leading engine manufacturers have developed technologies able to fulfil the existing and future regulations. The ACERT and slide-valve technologies, together with application of water-in-fuel emulsion, selective catalytic reduction, and biodiesel fuels represent comprehensive and efficient solutions.

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