

Assessment of Current and Future Air Pollutant Emission Reduction Technologies for Marine Diesel Engines

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Defence Research and Development Canada, Atlantic Research Centre

Contract Report
DRDC-RDDC-2014-C10
February 2014

Report Documentation Page				Form Approved OMB No. 0704-0188	
Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.					
1. REPORT DATE FEB 2014		2. REPORT TYPE		3. DATES COVERED 00-00-2014 to 00-00-2014	
4. TITLE AND SUBTITLE Assessment of Current and Future Air Pollutant Emission Reduction Technologies for Marine Diesel Engines				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S)				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) 3GA Marine Associates, 505-827 Fairfield Rd, Victoria, British Columbia V8V 5B2,				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT Defence Research and Development Canada (DRDC) has identified several air pollutant emission control technologies, which have potential for application to marine diesel systems. 3GA Marine Ltd (3GA) identified relevant technologies, including commercially available and developmental technologies. The technologies were catalogued, critically reviewed, and assessed to determine their maturity (Technology Readiness Level/TRL). It was concluded that a majority of identified technologies are mature and commercially available; however, some of them have a limited demonstration of performance. Only a few technologies were found to be new or emerging. Most of the air pollutant emission control technologies focus on reducing concentration of nitrogen oxides (NOx), sulphur oxides (SOx), or particulate matter (PM). Some reductions of concentration of the other air pollutants, including black carbon (BC), carbon monoxide (CO) or carbon dioxide (CO2) from the marine diesel systems is being achieved by these technologies. Several technologies can be used simultaneously to achieve the best and the most comprehensive reduction of air pollutants emissions from the marine diesel system. The study identified the factors particular to naval diesels and the fuel used by them, and indicated which of the technologies have highest potential for application in Canadian naval vessels. Use of alternative fuels may be a viable non-technological method of reducing emission of air pollutant, primarily NOx, PM, and CO2 from the marine systems.					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT Same as Report (SAR)	18. NUMBER OF PAGES 48	19a. NAME OF RESPONSIBLE PERSON
a. REPORT unclassified	b. ABSTRACT unclassified	c. THIS PAGE unclassified			

IMPORTANT INFORMATIVE STATEMENTS

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Abstract

Defence Research and Development Canada (DRDC) has identified several air pollutant emission control technologies, which have potential for application to marine diesel systems.

3GA Marine Ltd (3GA) identified relevant technologies, including commercially available and developmental technologies. The technologies were catalogued, critically reviewed, and assessed to determine their maturity (Technology Readiness Level/TRL). It was concluded that a majority of identified technologies are mature and commercially available; however, some of them have a limited demonstration of performance. Only a few technologies were found to be new or emerging.

Most of the air pollutant emission control technologies focus on reducing concentration of nitrogen oxides (NO_x), sulphur oxides (SO_x), or particulate matter (PM). Some reductions of concentration of the other air pollutants, including black carbon (BC), carbon monoxide (CO) or carbon dioxide (CO_2) from the marine diesel systems is being achieved by these technologies. Several technologies can be used simultaneously to achieve the best and the most comprehensive reduction of air pollutants emissions from the marine diesel system.

The study identified the factors particular to naval diesels and the fuel used by them, and indicated which of the technologies have highest potential for application in Canadian naval vessels.

Use of alternative fuels may be a viable non-technological method of reducing emission of air pollutant, primarily NO_x , PM, and CO_2 from the marine systems.

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Executive summary

Assessment of Current and Future Air Pollutant Emission Reduction Technologies for marine Diesel Engines:

Alicja Rudzki; Andrew Carran;

Defence Research and Development Canada – Atlantic; February 2014.

Introduction or background: Defence Research and Development Canada (DRDC) retained 3GA Marine Ltd. (3GA) to conduct a study of current and future air pollutant emission reduction technologies for marine diesel engines.

All vessels generate air pollutant emissions that have detrimental impact on the local and global natural environment. Internationally, the International Maritime Organization (IMO) International Convention for the Prevention of Pollution from Ship (MARPOL 73/78) Annex VI regulate management of air pollutant emissions, namely Nitrogen Oxides (NO_x) and Sulphur Oxides (SO_x), prescribes sulphur content of fuel used and identifies Emission Control Areas (ECAs) worldwide. In Canada, the Canada Shipping Act 2001(CSA2001) *Vessel Pollution and Dangerous Chemicals Regulations* the Arctic Waters Pollution Prevention Act (AWPPA) *Arctic Shipping Pollution Prevention Regulations (ASPPR)* regulate emissions of air pollutants from ships and quality of fuel used onboard.

Naval vessels are exempted from the international, national and local environmental regulations. However, the Department of National Defence (DND) is committed to meet or exceed applicable International and Canadian legislation that aims to protect the natural environment. Therefore, DRDC researches and advances air pollution control technologies to ensure that state-of-the-art systems are installed onboard Canadian naval vessels.

Results: In this report 3GA reviews scientific reports on diesel air emission reduction studies and literature on commercially available technologies to compile information on the state-of-the art and innovative pollutant reduction technologies. Each identified technology has been critically assessed for its ability to control various air pollutants and the technology maturity level has been determined using the Technology Readiness Level (TRL) scale. The applicability for use onboard Canadian naval vessel is also assessed.

Significance: The study shows that there are several state-of-the-art and emerging technologies available for controlling emission of air pollutants either as add on technology to existing engines or as fundamental engine design measures. The majority of these technologies are designed to control emissions of Nitrogen Oxides (NO_x) and Sulphur Oxides (SO_x) that are regulated internationally and nationally. Some of the NO_x and SO_x control technologies require use of additional power, which may result in increased level of Carbon Dioxide (CO₂) and Carbon Oxide (CO) emissions. Several technologies have been found to be capable of reducing Particulate Matter (PM), Black Carbon (BC) and Hydrocarbons (HC), which is of special importance for the vessels that operate in the coastal areas and in the Arctic and Antarctic regions.

Two technologies, namely advanced Internal Engine Modifications (IEMs) and Selective Catalytic Reduction (SCR), were found to be a currently viable and available NO_x and SO_x emission controls applicable to Canadian naval vessels.

Basic IEM and scrubber technologies are not applicable to Canadian naval vessels, as they suite either slow speed engines or use heavy fuel.

Future plans: Several technologies require further research and development or more onboard testing before considering them viable for Canadian naval vessels. These include Humid Air Motor (HAM), Selective Non-Catalytic Reduction (SNCR), CSNO_x, Diesel Particulate Filters (DPF) and Plasma Reduction System.

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1 Introduction

1.1 Background

The marine diesel industry has initiated approaches to reduce pollutant emissions from ships' diesel engines. Such approaches include modification of fuel and air intake properties, modification of diesel combustion parameters, and physical and/or chemical treatment of exhaust gases. DRDC Atlantic identified air pollutant emission reduction technologies for marine diesel systems as an area for investigation.

This study provides an assessment of:

Studies and product literature on air pollutant/greenhouse gas emission reduction technologies for marine diesel engines; and

The state-of-the-art in diesel air emission reduction technology.

1.2 Method

The study was contracted to 3GA Marine Ltd. The researchers set out to:

1. Summarize product literature for commercially available marine diesel engine upgrades/retrofit packages that claim improvements in fuel efficiency and/or reduction of air pollutant emissions.
2. Review scientific literature reports of diesel air emission reduction studies. Reports were sought on:
 - a. Small scale laboratory experiments, such as those utilizing model diesel engine systems incorporating emission reduction technologies of interest.
 - b. Actual ship data in which air pollutant emissions have been measured after modification of diesel engine operating parameters, modification of fuels or charge air intake, and/or installation of exhaust treatment systems.
3. Critically assess the state-of-the-art in diesel air pollutant emission reduction technologies, including improved air and fuel intake systems, re-optimization of combustion processes, physical/chemical treatment of exhaust gases, fuel oxidation catalysis, and other diesel engine enhancements.
4. Identify innovative technologies that may find applications in reducing air pollutant emissions from marine vessels, including references to product literature and/or scientific literature reports of such technologies.

In carrying out the study, 3GA Marine sought to place the findings in the context of the Royal Canadian Navy's circumstances, which differ markedly from those of the commercial marine industry, which is the target market for many emissions reduction approaches.

2 Air Pollutants from Diesel Combustion

Exhaust gases from ships' engines have many constituents including the following pollutants. These substances contribute, in various degrees, to air pollution and pose human health risks.

2.1 Carbon Dioxide (CO₂)

CO₂ (along with water) is the largest combustion product from marine engines, and is an inevitable outcome of all hydrocarbon combustion. CO₂ is a greenhouse gas (GHG), defined as a gas in the atmosphere that absorbs and emits radiation within the thermal infrared range. This process is the fundamental cause of the greenhouse effect, a process by which thermal radiation from the Earth's surface is absorbed by atmospheric GHG, and is re-radiated in all directions. Since part of this re-radiation is back towards the surface and the lower atmosphere, it results in an elevation of the average surface temperature above what it would be in the absence of the gases. Without GHG, Earth's surface would average about 33°C colder than the present average of 14°C. Since the beginning of the Industrial Revolution, the burning of fossil fuels has contributed to a 40% increase in the concentration of carbon dioxide in the atmosphere from 280 ppm to 400 ppm, despite the uptake of a large portion of the emissions by various natural "sinks" in the carbon cycle. Since the early 20th century, Earth's mean surface temperature has increased by about 0.8°C, with about two-thirds of the increase occurring since 1980. It is anticipated that during the 21st century the global surface temperature is likely to rise a further 1.1 to 2.9°C for the lowest emissions scenario and 2.4 to 6.4°C for the highest [1].

2.2 Carbon Monoxide (CO)

CO is an inevitable outcome of hydrocarbon combustion. CO is not a GHG but it slows down removal of methane (CH₄, which is a GHG) from the atmosphere.

2.3 Sulphur Oxides (SO_x)

Amounts of SO_x in engine exhaust emissions are directly related to the sulphur present in fuel: the less sulphur content in the fuel, the less SO_x in the exhaust. SO_x cause acid rain and SO_x oxidation in the atmosphere results in formation of fine sulphur particles that cause smog and can be a significant threat to human health, including contributing to respiratory problems. SO_x emissions from shipping represent about 60% of global transport SO_x emissions.

2.4 Nitrogen Oxides (NO_x)

The amount of NO_x in engines' exhaust is a function of the temperature and (in) completeness of combustion. NO_x also cause acid rain and their oxidation in the atmosphere results in formation of fine nitrate particles that can be a significant threat to human health. Emissions of NO_x from shipping represent about 40% of global transport NO_x emissions.

2.5 Particulate Matter (PM)

PM is emitted as a result of the incomplete combustion of fuel.

2.6 Black carbon (BC)

BC is a constituent of particulate matter (PM). BC generally constitutes between 5% and 15% of PM emitted by ships. BC is considered of particular concern in Polar Regions, in that BC deposited on ice and snow surfaces contribute to the surfaces absorption of radiated energy (sunlight) and thereby increases the rate of melting.

2.7 Methane (CH₄)

Methane is generated in small amounts during incomplete diesel combustion. Methane is a potent GHG.

2.8 Non-methane volatile organic compounds (NMVOCs)

NMVOCs, which include ethane, propane and butane, are also generated in small amounts during incomplete diesel combustion. NMVOCs contribute to the formation of tropospheric ozone, a GHG.

3 Emissions Requirements

3.1 Naval

Navies in general are exempt from national and international regulations, and the Royal Canadian Navy (RCN) does not have internal requirements to restrict air emissions. However, the RCN has repeatedly expressed its intention to be seen as a “good corporate citizen” and to voluntarily conform to international and Canadian civilian regulations in such areas as environmental protection. This intention is expressed in the requirements documents for future naval ships such as the Joint Support Ship (JSS) and Arctic/Offshore Patrol Ship (AOPS), which have international emission regulations written into their specifications. Therefore, it can be taken that the RCN’s intent is to comply with appropriate non-naval emissions requirements.

3.2 Non-Naval: International

Regulation of non-territorial waters is under the jurisdiction of the International Maritime Organization (IMO). IMO is a United Nations specialized agency and is responsible for the safety and security of shipping and the prevention of marine pollution by ships. In 1973, IMO adopted the International Convention for the Prevention of Pollution from Ships, now known universally as MARPOL. MARPOL includes Annexes relating to various types of pollution, and Annex VI, first adopted in 1997, limits the main air pollutants contained in ships exhaust gas, including sulphur oxides (SO_x) and nitrogen oxides (NO_x), and prohibits deliberate emissions of ozone depleting substances. MARPOL Annex VI also regulates shipboard incineration, and the emissions of volatile organic compounds from tankers.

Following entry into force of MARPOL Annex VI on 19 May 2005, the Marine Environment Protection Committee (MEPC), at its 53rd session (July 2005), agreed to revise MARPOL Annex VI with the aim of significantly strengthening the emission limits in light of technological improvements and implementation experience. Following three years of examination, MEPC 58 (October 2008) adopted the revised MARPOL Annex VI and the associated NO_x Technical Code 2008, which entered into force on 1 July 2010.

The main changes to MARPOL Annex VI are a progressive reduction globally in emissions of SO_x, NO_x and particulate matter and the introduction of emission control areas (ECAs) to reduce emissions of those air pollutants further in designated sea areas. Presently the North Sea, the Baltic and the non-Arctic coastlines of the USA and Canada are ECAs. Other ECAs are being considered, as shown in Figure 1[2].

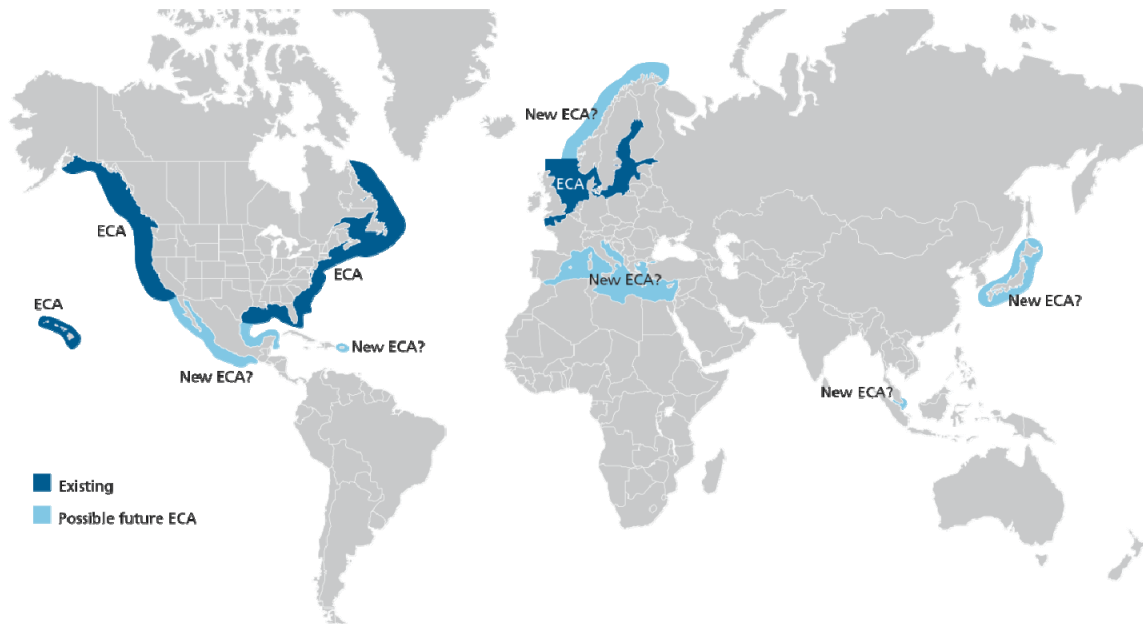


Figure 1: Current and Potential Emission Control Areas (ECAs) as defined by the IMO

3.2.1 Sulphur Oxides Emissions

Under the revised MARPOL Annex VI, the global sulphur cap was reduced initially to 3.50% (from 4.50%), effective from 1 January 2012; then progressively to 0.50 %, effective from 1 January 2020, subject to a feasibility review to be completed no later than 2018. The limits applicable in ECAs for SO_x and particulate matter were reduced to 1.00%, beginning on 1 July 2010 (from the original 1.50%); being further reduced to 0.10 %, effective from 1 January 2015. This information is presented in Table 1. The reduced sulphur requirements are written in terms of Fuel Oil Maximum Sulphur content, and the petroleum industry is increasing the availability of low-sulphur distillate fuels to the marine industry. However, the ocean-going marine industry historically uses residual fuel (or blends of residual and distillate fuels), which is typically half the price of low-sulphur distillate fuel. Consequently, there is considerable interest in alternate technologies to achieve the same reduction in sulphur emissions while burning higher sulphur fuels, which is allowed by MARPOL Annex VI.

Table 1: MARPOL Annex VI SO_x Reductions

Locations	Dates	Fuel oil maximum sulphur content:
Outside ECA-SO _x	To 31 December 2011	4.50%
	From 1 January 2012	3.50%
	From 1 January 2020 (subject to review)	0.50%
Inside ECA-SO _x	To 31 December 2014	1.00%
	From 1 January 2015	0.10%

3.2.2 Nitrogen Oxides Emissions

Progressive reductions in NO_x emissions from marine diesel engines installed on ships are also included, with a “Tier II” emission limit for engines installed on or after 1 January 2011; then with a more stringent “Tier III” emission limit for engines installed on or after 1 January 2016 operating in ECAs. Marine diesel engines installed on or after 1 January 1990 but prior to 1 January 2000 are required to comply with “Tier I” emission limits, if an approved method for that engine has been certified by an Administration.

The revised NO_x Technical Code 2008 includes a new chapter based on the agreed approach for regulation of existing (pre-2000) engines established in MARPOL Annex VI, provisions for a direct measurement and monitoring method, a certification procedure for existing engines, and test cycles to be applied to Tier II and Tier III engines.

3.2.3 Other emissions

Revisions to the regulations for ozone-depleting substances, volatile organic compounds, shipboard incineration, reception facilities, and fuel oil quality have been made with regulations on fuel oil availability added.

3.3 Non-Naval: Canada

In addition to the North American ECA, agreed internationally via IMO, Canada and the USA have agreed that the Great Lakes and St Lawrence Seaway will eventually adopt the same limits as an ECA. Transport Canada (TC) is allowing compliance to be phased in at a slower rate in recognition of the large number of legacy vessels in the Great Lakes area. The Canadian Great Lakes fleet is of considerable age and owners have been replacing inventory only slowly in recent decades. Great Lakes shippers have alternative transport modes available to them, and Great Lakes ship owners have stated that immediate replacement of the Canadian Fleet (and US owners

are of similar view) cannot be achieved. Therefore, TC introduced (Ship Safety Bulletin 06/2013) a regime of Fleet Average compliance with sulphur emissions levels which will be reduced year-by-year from 2012 to 2020 [3]. Compliance with fuel sulphur limits will be assessed based on the average of total sulphur emissions of fuel used across a company's entire fleet over a one-year period. The limits are 1.5% sulphur content fuel starting on August 1, 2012, 1% fuel sulphur by January 2015, and 0.1% fuel sulphur by 2020, on a declining basis as per Table 2:

Table 2: Great Lakes Annual Average Sulphur Fuel Limits Under TC Fleet Averaging Approach

Year	2012	2013	2014	2015	2016	2017	2018	2019	2020
Sulphur limit (fleet average)	1.6%	1.3%	1.2%	1.0%	0.8%	0.6%	0.5%	0.3%	0.1%

Fleet Averaging would cease in 2020: at that time all vessels in a fleet would be required to individually comply with the ECA-level performance standards (0.1% sulphur fuel). Although the initial date for this program has passed, it has not yet been implemented. However, it remains TC's intention to do so.

Canada's Arctic Waters Pollution Prevention Act (AWPPA) aims to prevent pollution in Canadian Arctic waters (defined as north of 60 deg latitude). The AWPPA is a 'zero discharge' act, which states, "no person or ship shall deposit or permit the deposit of waste of any type in the Arctic waters." The AWPPA has two key regulations, namely; the Arctic Shipping Pollution Prevention Regulations (ASPPR), and the Arctic Waters Pollution Prevention Regulations (AWPPR). However, the AWPPA, ASPPR and AWPPR, were drafted in 1970 and they are silent on air emissions. TC is currently considering updating the AWPPA and the regulations, and such updates may include making the Canadian Arctic an ECA.

4 Emission Control Technologies

Diesel engine emission control technologies can be divided into two principal classes: internal modifications to the engine design itself and add-on technologies. Add-on technologies may be subdivided into pre-combustion (applied to the air or fuel at the intake side of the engine) and post-combustion (treatment of the exhaust gas stream). Some diesel engine emission control technologies are already commercially available to marine operators while others are still emerging. In all cases, however, development is ongoing and the state of the art is advancing continuously.

Internal changes to the engines are generally preferable to exhaust treatment, as external treatment generally incurs additional costs, space limitations, extra consumables and increased fuel consumption (which has environmental – especially GHG – implication as well as financial).

4.1 Internal Engine Modifications

Internal Engine Modifications (IEMs) involve changes to the combustion processes. Some technologies are more suited (or are only suited) to one type of engine, while others are applied to many types. These include:

- Improved injectors (slide valves)
- Improved fuel injection systems (i.e. common rail)
- Modified turbochargers
- Low intake temperature
- Higher compression ratio, cylinder pressure and charge pressure
- Reduced nozzle hole size and increased number of nozzle holes for more rapid fuel/air mixing

4.1.1 Large Slow-Speed Engines:

The major manufacturers of large slow speed 2-stroke marine engines have replaced conventional fuel valves with **low NO_x slide valves**. Low NO_x slide valves optimize fuel spray distribution in the combustion chamber without compromising on component temperatures or engine reliability. Slide valves reduce Black Carbon by between 25% and 50%, and NO_x by approximately 10% to 30%. Currently, this IEM is limited to slow-speed 2 stroke engines only; all new engines of this type are thought to have these valves fitted as standard.

Technology Readiness Level: Low NO_x slide valves are proven emission reduction technology for new and retrofitted slow-speed marine engines. Therefore, this technology is assessed at TRL 9.

Supporting Technical Evaluation Data: Tests of effectiveness of low NO_x slide valve combined with modified fuel nozzle conducted by MAN on the engine at 90% Maximum Continuous Rating indicate that 23% reduction of NO_x emission can be achieved with a 1% fuel consumption increase; tests of low NO_x slide valve on slow speed engine conducted by Mitsubishi show reduction of 81% with 2% fuel consumption penalty [4].

Currently, MAN Diesel & Turbo supplies two-stroke engines with slide fuel valves, resulting in improved low load operating capabilities and reduced NO_x, HC (Hydrocarbons) and PM in engine exhaust emissions.

4.1.2 All engines, including medium and high speed 4-stroke engines:

Current engines generally benefit from all the technologies listed in 4.1, configured as appropriate for the engine type and duty. A combination frequently used is that of increased compression ratio, adapted fuel injection, valve timing and different nozzles. A reduction of 30-40% in NO_x emissions is generally achieved. For example:

Wärtsilä employs a combination of retarded injection, Miller cycle valve timing, higher compression ratio, increased turbo efficiency, higher max cylinder pressure and common rail injection.

Caterpillar combines higher compression ratio with higher cylinder pressure, higher charge pressure and flexible injection system.

FMC uses a combination of two-stage injection, Miller cycle valve timing, greater stroke/bore ratio, adjustable compression, two-stage turbocharging and low intake temperature

Technology Readiness Level: Advanced IEMs and their various combinations are assessed to be at TRL 9.

Supporting Technical Evaluation Data: IEMs are being researched and technically advanced by engine manufacturers who incorporate them into new engine designs and make them available as retrofit packages for existing engines. The German government-funded the Emission Minimisation research project, which focused on optimising the Caterpillar Common Rail (CCR) system to achieve further NO_x emission reduction from MaK Low Emission Engine (LEE). The study investigated the influence of nozzle flow on fuel mixture formation (droplet break up and distribution) and its impact on emissions. It was found that to achieve NO_x emission reduction of 50% below IMO Tier I (or 10% below Tier II) requirements, a combination of electronically controlled injectors with multiple injection capabilities and adjustment of compression ratio and charge air temperatures have to be done. These adjustments may result in an efficiency drop of 2% to 3% and increased smoke emissions. The same study indicated that combination of higher compression ratio and stronger Miller Cycle can result in NO_x emission reduction fulfilling the requirements of IMO Tier III [5]. However, the 2012 study published by National Research Canada states that the combination of advanced IEMs amounts to a 20 – 30% reduction in NO_x emissions which is insufficient to meet IMO Tier III standards [6].

4.2 Add-on technologies

Add-on technologies have been developed (and continue to be developed) to treat either the input fluids (air/fuel) prior to combustion or the exhaust streams after combustion to reduce one or more types of pollutant.

4.2.1 NO_x reduction technologies

Most engine modifications in recent designs can meet IMO Tier II NO_x requirements without after-treatment. However, to meet IMO Tier III NO_x, an emissions treatment system is currently required. Technologies that address NO_x include:

Humid Air Motor (HAM)

Selective Catalytic Reduction (SCR)

Selective Non-Catalytic Reduction (SNCR)

CSNO_x (also designed to reduce SO_x and carbon emissions)

Water in Fuel Injection (WiFE) on Demand

Exhaust Gas Recirculation (EGR)

Combustion Air Saturation System (CASS)

Diesel Particulate Filters (DPF)

Plasma Reduction System

4.2.1.1 Humid Air Motor (HAM)

The HAM system consists of a humidifier, circulating pump, heat exchanger and may require a treatment system for controlling mineral content of the make-up water. HAM is an alternative to water injection; it uses seawater or fresh water to make air that is almost 100% saturated with water vapour (humid air) that has almost twice the heat capacity of dry air, which allows for absorption of the heat generated in the compression chamber that in turn reduces NO_x formation by 20% to 80% and BC by up to 50%. According to the system manufacturer, application of HAM slightly increases specific fuel consumption and the presence of smoke in the exhaust gas. HAM may underperform at low load, when there may not be sufficient heat to evaporate the required volume of water; also, it may be difficult to control the humidity under varying loads of the engine. These issues have yet to be solved.

HAM technology is being advanced and potentially offered to marine operators by MAN Diesel & Turbo. MAN states it has conducted over 100, 000 hours of onboard and land based testing of this technology.

Technology Readiness Level: HAM technology has been extensively tested onboard ships; however, its commercial implementation is still awaited. HAM technology remains under development for shipboard application; therefore, it is assessed to be at TRL 7.

Supporting Technical Evaluation Data: Demonstration tests of the commercially available engines indicate that HAM technology can reduce NO_x emissions by 60% to 80% [7]. Shipboard installations of HAM technologies show NO_x reduction capabilities of 70% to 84% [8]. MAN Diesel & Turbo states that their HAM systems installed on main engines onboard ships reduce emissions of NO_x by 62% to 68%.

While reduction of NO_x formation results primarily from reduction of combustion air temperature, some reduction of NO_x can be attributed to dilution of air thus lowering excess oxygen in the cylinder. HAM appears to reduce hot spots in diesel engines without reducing the engine's efficiency. Also, less stress on exhaust valves, cleaner combustion chambers and reduced lube oil use are observed when using HAM. HAM combined with water fuel emulsion or direct water injection systems can offer further NO_x reductions [7].

HAM is not affected by sulphur content of fuel, which makes this technology more advantageous than the other NO_x control systems.

HAM has high initial costs, as it requires installation of the humidifier, which additionally occupies a large space. Water treatment may be required to control the level of minerals and prevent their deposition in the system [9].

4.2.1.2 Selective Catalytic Reduction (SCR)

SCR uses a catalyst to convert NO_x emissions into nitrogen and water by injecting ammonia (NH_3) or urea solution ($\text{CO}(\text{NH}_2)_2$) in the exhaust gas at a temperature of $290^\circ\text{C} - 350^\circ\text{C}$. Use of SCR can result in a reduction in NO_x emissions of up to 90-92% and PM reduction by 25% - 40%, which leads to reduction of BC.

The SCR equipment is comprised of a pump unit to transfer and regulate urea to the dosing unit located in the exhaust pipe. The dosing unit also requires compressed air to atomize the urea from the injector into the exhaust stream. The injected urea is distributed throughout the exhaust stream in a mixing pipe before reaching the reactor (SCR), where the catalytic reduction takes place. The reactor houses the catalyst elements, soot blowing outlets, and NO_x monitoring equipment. The catalyst elements are rectangular-shaped honeycomb structures made up of vanadium pentoxide (V_2O_5). The efficiency of the catalyst decreases with time, mainly due to thermal load and declining amounts of catalyst. Eventually the catalyst must be changed. The lifetime of the catalyst depends on the fuel type and other operating conditions. The typical lifetime is 4 - 6 years. (Wärtsilä Finland Oy, 2012). According to Wärtsilä, SCR is the most viable technology for achieving Tier III NO_x compliance and MAN Diesel & Turbo also claims that their engines achieve Tier III NO_x compliance with the use of an SCR system.

Despite the high investment cost estimated at 30-50 Euro/kW and operating cost is 5-8 Euro/MWh, in long term the SCR is considered to be the most efficient method of NO_x reduction [10].

SCRs for new and retrofitted marine diesel engines are being designed and offered by most marine diesel companies.

Technology Readiness Level: SCR technology is a viable solution for four-stroke medium and high-speed diesel engines and has been already installed on more than 400 ships. SCR technology is expected to be a commonplace, commercially available solution by 2014, and is the most likely solution to be adopted in meeting IMO NO_x Tier III requirements for engine installations in ships operating in Emission Control Areas from 1 January 2016. This technology is assessed to be at TRL 9.

Supporting Technical Evaluation Data: Emission testing conducted on the auxiliary, four stroke, medium speed marine diesel engines installed onboard ocean going container vessels indicate that when sulphur content of fuel varies between 0.05 % m/m and 0.263 % m/m, the following emissions reductions can be achieved [11]:

NO_x reduction by 82%-84%

BC reduction by up to 20%

CO increased by a factor of 1.4 – 2

$\text{PM}_{2.5}$ increase by 89%-92%

Laboratory studies show that SCR systems reduce NO_x by up to 95% when low sulphur bunker oil is combusted at temperatures above 300°C [12].

Testing conducted on a two-stroke DDC 4-71 diesel engine and four stroke Cummins 5.9L B series engine showed 80%-90% reduction of NO_x [13]. To ensure the temperature is high enough, the catalytic converter may have to be installed between the engine exhaust gas receiver and the turbocharger [12]. The most critical problems are the space requirement for the catalyst elements, storage of ammonia or urea, and potential for ammonia slip that in the case of high sulphur fuel use may lead to formation of sulphurous and sulphuric acids causing corrosion in the exhaust system. Ammonia slip is most likely to happen during changes in engine loading while the urea dosing is varied in an attempt to match the engine speed [6, 14].

SCR installation does not require changes to the engine design and it is not detrimental to the engine operation [4]. SCR can take the place of (or reduce the requirement for) exhaust mufflers, since SCR gives sound attenuation up to 40 dBC(A).

4.2.1.3 Selective Non-Catalytic Reduction (SNCR)

SNCR works in a similar way to Selective Catalytic Reduction but without the use of a catalyst. A reducing agent (ammonia or urea) injected during the combustion process converts the nitrogen oxides into nitrogen and water, reducing NO_x emissions by up to 50% [15].

Tests indicate that NO_x removal improves with increasing temperature and pressure, which indicates that SNCR may be a viable method for gas turbines[13].

Technology Readiness Level: SNCR is assessed to be at TRL 6.

Supporting Technical Evaluation Data: SNCR appears to be less efficient than SCR because only 10-12% of the injected ammonia reacts with NO_x and the rest is burned out. To achieve 50% reduction of NO_x it requires four times the stoichiometric amount of NH_3 [16, 17]. SNCR systems require high temperatures ($900^\circ\text{C} - 1000^\circ\text{C}$) and long combustion time. When the combustion temperature exceeds 1000°C production of NO_x increases and when temperature falls below 900°C ammonia slippage occurs. Installation of SNCR requires extensive modification to the engine.

4.2.1.4 CSNOx

CSNOx (a proprietary name for a technology developed by Ecospec) is a novel technology scrubber system. Most scrubber systems (see section 4.2.2) are designed for SO_x removal, but CSNOx uses fresh or saltwater that at first undergoes ultra-low frequency electrolysis to increase NO_x absorption capability and then is pumped through the exhaust stack to scrub emissions of SO_x , NO_x and CO_2 . The resulting scrubbed water can be either discharged overboard or treated and reused in the system.

Technology Readiness Level: CSNOx has been verified by ABS for SO_x effectiveness when burning HFO with sulphur content of 3.64%. It has been installed on a Canada Steamship Lines carrier in 2012 and the testing of its performance continues. This technology is assessed to be at TRL 7.

Supporting Technical Evaluation Data: Water used in the CSNOx system has to be treated to prevent bio fouling. The CSNOx process comprises of two distinctive stages. In the first stage, scrubbing water passes through the SO_x absorption enhancer and then is sprayed into the

treatment tower to remove SO₂ from the exhaust gases. In the second stage, scrubbing water passes through a series of treatment units that enhance CO₂ and NO_x removal ability and prevent mineral deposits in the system, and then is sprayed into the treatment tower to remove pollutants. When tested on a trading 100,000-tonne Aframax tanker, the CSNOx system demonstrated that it is capable of removing simultaneously up to 99% of SO_x, 66% of NO_x and 77% of CO₂ from engine air emissions [18, 19]. This performance was verified by the American Bureau of Shipping as part of the ongoing IMO Type Approval certification process by Ecospec. The impact of CSNOx system use on ship energy consumption has not been determined yet [10].

4.2.1.5 Water in Fuel Emulsion (WiFE) on Demand

Emulsification on demand consists of introducing water and emulsifier into the fuel prior to injection into the combustion chamber. Emulsified fuel leads to a more effective atomization and a better distribution of the fuel in the combustion chamber, which results in more complete combustion. WiFE simultaneously reduces levels of NO_x and PM in engine exhausts emissions. WiFE has been in use since the 1980s when MAN B&W Diesel tested effectiveness of water in fuel emulsion on NO_x emissions; however, its application in ships is still very limited.

Technology Readiness Level: Considering the TRL definition and descriptions, WiFE is assessed at TRL 8.

Supporting Technical Evaluation Data: WiFE can be retrofitted to a variety of vessel types and fuel systems and it can work with a variety of water-to-fuel ratios, from 0% to 50%. An emulsion of 30% of water in fuel can reduce NO_x emissions by 30%-60%, PM by 60-90% and BC by 45% - 50% [8, 20]. By combining WiFE with exhaust gas recirculation, NO_x emissions may be reduced by more than 90% and the emissions of CO and HC maintained at low levels [21].

Corrosion of fuel systems may occur and its severity depends on water to fuel ratio and type and concentration of emulsifier used in the system. Water used in the system must be distilled to remove compounds that may react with fuel causing fouling of the fuel injectors and exhaust system. For better efficiency of treatment, fuel oil supply pressure might be increased, which might require strengthening of the engine. Water has to be dosed without causing fluctuation in the temperature in the combustion cylinders [9]. Application of WiFE requires use of diesel fuel additives, installation of an emulsifying unit, and a water temperature control system. Finally, the WiFE system appears to increase the specific fuel oil consumption by 0.5% to 2%, which results in a proportional increase of CO₂ emission [22].

4.2.1.6 Exhaust Gas Recirculation (EGR)

EGR involves re-burning the exhaust gas. In this process, a portion of exhaust gases is filtered, cooled and circulated back into the engine's charge air, which decreases the cylinder temperature and thus reduces the formation of NO_x during the combustion process. Application of EGR reduces engine efficiency and thus increases specific fuel consumption, which in turn leads to increased CO, HC and PM emissions.

MAN Diesel indicates in their technical brochures that EGR can reduce NO_x by 80%; according to Wärtsilä, this reduction may be as high as 90%.

Technology Readiness Level: Considering the TRL definition and descriptions, EGR is assessed at TRL 8.

Supporting Technical Evaluation Data: EGR in marine diesel engines using turbochargers utilizes the differences between the scavenge and exhaust pressure and therefore it requires installation of an additional exhaust blower.

Recirculation of exhaust gases containing soot causes contamination of lubrication oil, leading to reduced oil viscosity. This reduces the lubricating properties of the oil, which eventually may lead to increased noise and wear of the engine; additionally, exhaust gases contain gaseous sulphur species that form sulphuric acid, causing corrosion problems [9]. Presentations to the cruise industry in 2009 by MAN Diesel showed badly contaminated exhaust valves in engines after only a few hundred hours operation with EGR. Therefore MAN considered that installation of a scrubber to remove pollutants from the exhaust gases would be needed prior to recirculating them.

MAN Diesel & Turbo tested EGR with scrubber and water treatment for cleaning the recirculated exhaust gas before it entered the air cooler and the scavenge air system; combination of these systems resulted in reduction of PM by 20% - 25% with no impact on HC and CO content. They also determined, that when the EGR is applied at low engine speed, optimizing injection timing may minimize negative impact on engine efficiency; however, in high engine load reduced engine efficiency is irreversible [23].

4.2.1.7 Combustion Air Saturation System (CASS)

CASS is similar to HAM and other water injection systems. It uses a compressor to inject a pressurized mist of water into the engine intake air after it exits the turbocharger, which reduces the combustion temperature and thus provides a 30% to 60% reduction of NO_x. CASS does not appear to increase fuel consumption and does not require engine modifications. However it has high water consumption.

Wärtsilä was the sole developer of CASS technology and no information on the actual shipboard installation was found. No recent information on CASS has been released by the company.

Technology Readiness Level: Considering the TRL definitions and limited information on the CASS applications, this technology is assessed at TRL 6.

Supporting Technical Evaluation data: CASS technology may no longer be under development. No technical studies of the system could be obtained.

4.2.1.8 Plasma Reduction

Systems

The ability of plasmas to de-pollute exhaust gases has been established and is in full scale development [25], including for marine engines [26]. Potential systems introduce plasmas into the exhaust stream, typically by dielectric barrier discharge (DBD) reactors. DBD reactor electrode geometries may be cylindrical or planar, or may use a packed bed with special pellet filling. Plasma treatment may be used alone or in conjunction with selective catalytic reduction. In the latter case, plasma improves the performance of the catalysts at temperatures below 200-300°C [27-29].

Principles

Plasma is an ionised gas containing electrons, ions and neutral species (atoms and molecules). Although the particles are unbound, they are not ‘free’: when the charges move they generate electrical currents with magnetic fields, and as a result, they are affected by each other’s fields. Therefore, plasmas are characterized by collective behaviour with many degrees of freedom. Plasma is often referred as the “fourth state of matter” since it has unique physical properties distinct from solids, liquids and gases. In particular, due to the presence of charge carriers plasmas are electrically conductive and respond strongly to electromagnetic fields. Plasmas also contain chemically reactive media. Plasmas are classified as “thermal” or “non-thermal”. In thermal plasmas, electrons, ions and neutral particles are all at the same temperature, i.e., they are in thermal equilibrium with each other. In non-thermal plasmas on the other hand, the ions and neutrals are at a much lower temperature (in “cold” plasmas, this can be room temperature) than the electrons [24].

In cold non-thermal plasmas the free energetic electrons are able to produce radicals and other reactive species (e.g. ions) that react with the pollutant molecules or particles. Many molecules are readily attacked by free radicals. Decomposition of hazardous compounds is achieved without heating of the flue or off-gas. Due to the presence of oxygen, water vapour and ozone, oxidizing reactions are dominant. The resulting chemistry is complex and depends on the gas mixture itself as well as the temperature. Furthermore, if ions can be extracted from the discharge, fine particles can be charged and thus filtered electrically from the flue gas [25].

Technology Readiness Level: Considering the TRL definitions and information on plasma reduction systems, this technology is assessed at TRL 6.

Supporting Technical Evaluation Data: *Non-thermal plasma (NTP)* was shown to reduce emissions of both NO_x and particulate matter (PM). The effective partial oxidation of NO to NO₂ in plasmas has been widely demonstrated [30]. Experiments have shown that Plasma Reduction Systems can reduce NO_x by up to 97 % [12, 26]. The US Office of Naval Research treated the exhaust of a 750 kW diesel generator at Port Hueneme Naval Facility using a reactor of 40 cm length and 10 cm diameter. The NTP treatment comes at an energy cost: the ONR’s results showed the reactor consumed approximately 2% of the generator’s power output [13], hence the NO_x and PM improvement is associated with higher GHG emissions.

Plasma Assisted Catalytic Reduction (PACR) tested in the laboratory on a marine diesel engine reduced NO_x in engine exhaust by over 90% [31].

4.2.2 SO_x reduction add-on technologies

Although there are several manufacturers offering a variety of solutions, all SO_x exhaust gas treatment systems rely on “scrubbing” the exhaust gas stream by exposing it to an absorber, either water (with or without additives) or a dry chemical. The absorber removes a large proportion of the SO_x present in the exhaust stream, transferring it to a medium that can then be treated and discharged. Scrubber technology is very mature in land based systems, such as power generation plants, and has been trialed on ships over the last fifteen years or so. Use of scrubbers for SO_x reduction (in lieu of using low sulphur fuel) has been recognised by IMO through MARPOL. MEPC 184(59) “Guidelines for Exhaust Gas Cleaning Systems” was issued in 2009 to specify the requirements for the test, certification and in-service verification of SO_x scrubbing systems [32].

There are two main types of SO_x scrubber:

- wet scrubbers that use water (seawater or fresh) as the scrubbing medium; and

dry scrubbers that use a dry chemical (e.g. Couple Systems GmbH - Dry EGS).

Wet systems are further divided into:

‘open loop’ systems that use seawater (e.g. Krystallon)

‘closed loop’ systems that use fresh water with the addition of an alkaline chemical (e.g. Wärtsilä scrubber, Clean Marine); and

‘hybrid’ systems that can operate in both open loop and closed loop modes (e.g. Alfa Laval Aalborg PureSO_x, Green Tech Marine).

4.2.2.1 Wet SO_x scrubbers – open loop

In wet open loop SO_x scrubbing systems (including hybrid systems operating in open loop mode) seawater is pumped from the sea through the scrubber, cleaned and then discharged back to sea. Washwater is not recirculated. The washwater flow rate in open loop systems is approximately 45m³/MWh. SO_x removal rate is close to 98% with full alkalinity seawater, meaning emissions from a 3.50% sulphur fuel will be the equivalent of those from a 0.10% sulphur fuel after scrubbing. In the design process seawater temperature also has to be considered as SO₂ solubility reduces at higher seawater temperatures. Since the effectiveness of the scrubber is due to exposing the exhaust gas to an alkali, water of low salinity, and therefore lower alkalinity, is ineffective as a scrubbing medium. This means that open loop systems are not appropriate for fresh water (such as the Great Lakes) or lower salinity seas such as the Baltic [32].

4.2.2.2 Wet SO_x scrubbers – closed loop

All marine closed loop SO_x scrubbers (including hybrid SO_x scrubbers when operating in closed loop mode) use fresh water treated with sodium hydroxide (NaOH) as the scrubbing media. This results in the removal of SO_x from the exhaust gas stream as sodium sulphate. Rather than the once-through flow of an open loop scrubber the washwater from a closed loop scrubber passes into a process tank where it is cleaned before being recirculated. Control of pH by dosing with sodium hydroxide enables the washwater circulation rate and therefore power consumption to be about half that of open loop systems at approximately 20 m³/MWh and between 0.5% and 1% of the power of the engine being scrubbed.

Closed loop systems can also be operated when the ship is operating in enclosed waters where the alkalinity would be too low for open loop operation.

Closed loop systems discharge small quantities of treated washwater to reduce the concentration of sodium sulphate. If uncontrolled, the formation of sodium sulphate crystals will lead to progressive degradation of the washwater system. Information from scrubber manufacturers suggests that the washwater discharge rate is approximately 0.1 m³/MWh.

The rate of fresh water replenishment to the system is not only dependent on the discharge to sea but also losses to the exhaust through evaporation and via the washwater treatment plant. The rate of evaporation is influenced by exhaust and scrubbing water temperatures, which in turn are governed by factors such as engine load and the temperature of the seawater supply to the system coolers. Some of the water vapour incorporated within the exhaust may be captured after the scrubber and reused to reduce fresh water consumption.

With the addition of a washwater holding tank, closed loop systems can operate in zero discharge mode for a period of time (the exact length of time depends on the size of the holding tank). This flexibility is ideally suited to operation in areas where there is sensitivity to washwater discharges, such as ports and estuaries.

Closed loop systems typically consume sodium hydroxide in a 50% aqueous solution. The dosage rate is approximately 15 litres/MWh of scrubbed engine power if a 2.70% sulphur fuel is scrubbed to equivalent to 0.10%.

4.2.2.3 Wet SO_x scrubbers – hybrid

Wet scrubber systems generate hydrocarbons (PAH's) and particulate matter (PM) that end up in the scrubber effluent. The EnScrub Biofilter addresses these contaminants. As such, it is an add-on device to SO_x scrubber systems to help keep ship owners in compliance with both clean air and clean water standards [33]. The EnScrub Biofilter was successfully tested in 2011 and shipboard testing is currently underway.

4.2.2.4 Dry SO_x scrubbers

Dry SO_x scrubbers have been widely used in land based industries since the 1970s. A scrubber unit, in this case known as an 'absorber', brings the exhaust gas from one or more combustion units into contact with calcium hydroxide granules. Unlike the majority of wet scrubbers, the exhaust gas entry is perpendicular to the vertical downward flow of the scrubbing medium. No heat is removed from the exhaust gas during scrubbing (in fact the reaction is exothermic and releases heat) so dry scrubbers can be positioned before waste heat recovery and SCR equipment.

Dry scrubbers typically operate at exhaust temperatures between 240°C and 450°C. Calcium hydroxide granules are between 2 and 8 mm in diameter with a very high surface area to maximise contact with the exhaust gas. Within the absorber, the calcium hydroxide granules (Ca(OH)₂) react with sulphur oxides to form gypsum and water (CaSO₄·2H₂O). Used granules are retained on board, and suppliers of Dry SO_x scrubbers claim there is a modest market for the used granules in building materials.

Trials on a 3.6MW engine using up to 1.80% sulphur content fuel are reported to show a 99% and 80% reduction in SO₂ and particulate matter emissions respectively [32].

Technology Readiness Level: Scrubbers are being installed in new construction and conversions in increasing numbers (but still modest, compared to the global population of ships). There are a number of proponents of each type of scrubber technology, and Classification Society approval has been obtained for many types. The technology is assessed at TRL 9.

Supporting Technical Evaluation Data: The Exhaust Gas Cleaning Systems Association members have considerable evidence of successful scrubber installations [34]. The state of the art has moved in the last five years from demonstration installations to production orders, such as Norwegian Cruise Line which is building two cruise ships equipped with Green Tech Marine scrubbers [35] and Carnival Cruise Lines' announcement in September 2013 that 32 ships will be retro-fitted with scrubbers (of undetermined type) and particulate filters [36].

Onboard tests indicate that scrubbing technologies are very effective in removal of SO_x and PM from the engine exhaust [19], for example:

A Krystallon open loop system installed on Holland America's "Zaandam" removed approximately 75% of SO_x and 57% of PM [37]

An Ecospec CSNO_x system (which is in part a closed loop scrubber - see 4.2.1.4) installed onboard an oil tanker removed 99% of SO_x, 66% of NO_x and 77% of CO₂

A Wärtsilä closed loop system installed on the tanker “Suula” removed 99% of SO_x and 30-60% of PM

An Alfa Laval Aalborg hybrid system – Pure SO_x removed more than 98% of SO_x and up to 80% of PM

A Clean Marine AS closed loop system installed on a Klaveness bulk carrier removed more than 98% of SO_x

A Couple Systems GmbH – DryEGGS system installed on MS Timbus MAK 3.6 MW removed 99% of SO_x and 98% of PM

4.2.3 Particulate Matter (PM) reduction add-on technologies

4.2.3.1 Diesel Particulate Filter (DPF)

DPFs are after-treatment devices that collect PM from the exhaust system and periodically burn them off during the filter regeneration process. There are two types of DPF:

Active (require fuel burners or electronic current for the regeneration);

Passive (use catalysts to regenerate)

DPFs are effective only on engines using low sulphur fuel and they are the most efficient when fuel sulphur content is less than 0.05%. DPFs are capable of reducing PM emissions by 55 to 95% and BC emissions by 95 to 99%; however, they increase fuel consumption by up to 4%, which leads to increased CO₂ emissions [6].

Technology Readiness Level: DPF technology is assessed at TRL 7.

Supporting Technical Evaluation Data: Marine-X is a passive DPF that uses catalytically coated ceramic filters to trap particulate matter, which is then burned off as CO₂. These DPFs are quoted to reduce emissions of CO by up to 98% and diesel HC by 95%.

MTU has developed a passive DPF that uses the Continuous Regeneration Trap (CRT) for the continuous burning of diesel PM. The CRT may require occasional temperature boost to ensure effective soot burning, which may be achieved by increasing the exhaust temperature. The MTU DPF is designed for diesel fuel with very low sulphur content.

DPF technology has also been trialled in conjunction with a Non-Thermal Plasma (NTP) reactor (see 4.2.1.8) to decompose, by oxidation, accumulated PM into CO and CO₂ [26].

Several of the technologies designed primarily for NO_x and SO_x and described in 4.2.1 and 4.2.3 (e.g. SCR, scrubbers and plasma treatment systems) are also effective in reduction of PM and BC emissions.

5 Royal Canadian Navy diesel engines

There is a very large range of types of marine diesel engines, with power outputs of over 100MW down to a few kW for power generation or auxiliary propulsion of sailboats. Engines are often categorized by their rotational speeds into three nominal groups:

High-speed engines ($> 1,000$ rpm)

Medium-speed engines (300 - 1,000 rpm), and

Slow-speed engines (< 300 rpm)

High- and medium-speed engines are predominantly four-stroke cycle. Medium-speed engines generally have larger cylinder bores but fewer cylinders, and are heavier, than high-speed engines of the same power. Slow-speed engines are substantially larger again, and are predominantly two-stroke crosshead engines, hence very different from high- and medium-speed engines. Due to the lower rotational speed of slow- and medium-speed engines, there is more time for combustion during the power stroke of the cycle than high-speed engines, allowing the use of slower-burning fuels.

The majority of commercial vessels use slow speed engines in large ships where long steady-speed voyages are the norm (e.g. container ships, tankers, other cargo vessels) or medium speed engines where space is limited or a range of operational speeds is required (e.g. passenger vessels, tugs and supply vessels, fishing vessels). Naval vessels are usually very tightly constrained for space and require a large degree of operational flexibility, and their diesel engines are generally in the high speed category. In the context of this study, it is important to note that the majority of air emission reduction development has been for slow and medium speed engines burning commercial grade fuel, which is a different scenario to the RCN.

5.1 Present fleet

Brief information on the RCN's inventory of diesel engines is presented below. The navy's engines are all four-stroke compression-ignition types and (with the exception of the Halifax class propulsion diesel and some tugs etc.) in the high -speed range. All the RCN engine types are no longer in production, and probably present little opportunity for retrofit of Internal Engine Modifications for emissions reduction.

5.1.1 Warships

Diesel engines installed in the warship classes of the Royal Canadian Navy comprise the following:

5.1.1.1 Iroquois class Destroyers (three ships)

The Iroquois class propulsion plant uses gas turbines only, and therefore is outside of the scope of this study.

Electrical power generation as-built was also gas turbine-based, but some diesel generator capacity was added at mid-life.

5.1.1.2 Halifax class Frigates (twelve ships)

The Halifax class propulsion plant is a combination of two gas turbines and one mechanically-connected diesel engine. The diesel engine is a Pielstick PA6, twenty cylinder V-configuration, 28 cm cylinder bore, producing 5.5 MW @ 750 rpm.

Electrical power is produced by four generators, each powered by a high-speed MWM Deutz engine.

5.1.1.3 Kingston class Coastal Defence Vessels (twelve ships)

Electrical power for propulsion and ships services is provided by four generators each powered by a Wärtsilä UD 23 V12 engine delivering 780 kW at 1800 rpm.

5.1.1.4 Protecteur class Supply Vessels (two ships)

The Protecteur class propulsion and electrical power generators are steam turbine powered, therefore are outside the scope of this study.

5.1.1.5 Victoria class Submarines (four boats)

Each submarines' batteries are recharged by two diesel-powered generator sets. The diesels are Paxman (now MAN) Valenta RP200L V12 engines producing 1.5 MW at 1500 rpm.

5.1.2 Auxiliary Vessels

5.1.2.1 Orca class (eight ships)

Propulsion is provided by two Caterpillar 3516B marine diesel engines, each rated for 2,500 horsepower at 1,600 rpm. Electrical power is supplied by three 72 kW Caterpillar 3054 diesel generator sets.

5.1.2.2 Other

The RCN also operates a number of auxiliary vessels such as ocean-going tugs, harbour tugs and range patrol vessels. Such ships are powered by a variety of obsolete diesel engines, mainly high speed types.

5.2 Future fleet

5.2.1 Arctic/Offshore Patrol Ship

The AOPS class design was developed by BMT Fleet Technology and STX Canada Marine and the production design is currently being undertaken by Irving Shipbuilding Inc. The BMT/STX class design envisaged an integrated power plant for propulsion and is powered by four Wärtsilä 6L32 engines each developing 3.3 MW at 720 rpm. This engine selection may change for production, but the use of medium speed four-stroke engines is almost certain. AOPS is intended to meet MARPOL Annex 6 Tier III NO_x emissions. For this purpose, Selective Catalytic Reduction is mandated by the AOPS specification prepared by BMT/STX.

5.2.2 Joint Support Ship

The JSS will be a modified BERLIN class as is in service in the German Navy. The first two Berlin class ships were built in 1990/1992 with MAN Diesel 12V 32/40 medium-speed (750 rpm) engines, but the third ship was built in 2002 with MTU 20V 8000 M71R high speed (1150 rpm) engines producing higher power than the first two ships (7.2 MW). The switch to high speed allowed a higher power engine to be accommodated in the available space. The emissions specification for JSS is not available to these authors, but any commercial ship built after 2016 is to comply with Tier 3 for NO_x.

5.2.3 Canadian Surface Combatant

The power plant of the CSC is not yet known, but is likely to include diesel engines. Although gas turbines may also feature to address the maximum power conditions, the trend in warship design is to use diesel power for all but the few occasions when very high ship speed is required; therefore the bulk of the operating speed range is met by diesel power. Designers are starting to use medium speed diesels for warship propulsion, and this may be the case with CSC.

6 Royal Canadian Navy fuel

The RCN primary fuel is a NATO standardised fuel known as F-76. F-76 is discussed in section 6.2. To put the RCN's fuel in context we first describe commercial marine fuels.

6.1 Commercial Marine Fuel

6.1.1 Heavy fuel

Most deep-sea shipping, and a significant percentage of coastal shipping, has traditionally operated on heavy or medium fuels known as HFO (Heavy Fuel Oil) or IFO (Intermediate Fuel Oil) depending on composition. These fuel types contain residual product, which is what is left in the oil refining process after more valuable components have been extracted by some form of refining process. Residual fuel is less expensive than the crude oil from which it is derived, and considerably cheaper than refined (distillate) fuel. Heavy and medium marine fuels may be wholly residual or blends of residual and distillate fuels. As refining processes have become more efficient, the quality of the residuals has become worse and the percentage of the feedstock that emerges as residuals has reduced.

There are some specifications that any marine fuel is required to meet, but heavy fuels will typically include a wide range of contaminants, including:

- Ash
- Water
- Sulfur
- Vanadium
- Aluminum
- Silicon
- Sodium
- Sediment
- Asphaltenes

Some of these contaminants will be present in the crude oil itself and tend to become more concentrated in the residuals while others can be introduced by the refining process. In all cases, the contaminants entering the combustion processes in the fuel will emerge in some form in the exhaust gases. The combustion products are generally dangerous to the environment and to human health.

The poor quality of marine engine exhaust emissions have been recognized as a growing problem. In recent years, the shipping industry growth, the decreasing quality of heavy fuels and the increase in land-based emission regulations has led to the development of new international and more local requirements, as described in Section 3.

6.1.2 Marine diesel

Marine diesel oil (MDO) is quite different to the type of diesel fuel used by cars and trucks, being more viscous and having more impurities. The low and medium-speed diesels in widespread use in the marine industry operate at much lower speed (revolutions per minute) than road engines, and can, therefore, use fuels with lower cetane number (a measure of the ease of ignition).

Marine diesel is derived from crude oil by some form of distillation (differential boiling) process rather than by chemical cracking. Some mixing with less expensive heavy fuels is allowed provided the blended fuel stays within acceptable property ranges. Compared to heavy fuel, marine diesel has normally contained lower concentration levels of undesirable contaminants such as sulphur, but permissible levels have remained quite high until the recent advent of new national and international standards. In particular, the MARPOL Annex VI ECA requirements impose a limit of 0.1% by weight (1000 parts per million) on sulphur content of fuels from January 2015. MARPOL Annex VI allows alternate technology to be used in ships if the technology has the same effect on sulphur emissions as would be obtained by burning low-sulphur fuel.

6.2 NATO standard F-76

All NATO navies, including the RCN, have standardised on the use of distillate marine diesel fuel complying with NATO STANG-1385, known as F-76. The US standard for F-76 is MIL-DTL-16884M. The current standard is already compliant with ECA sulphur levels: the standard has progressively been revised as follows:

Spec Revision	date	maximum permissible sulphur content
MIL-DTL-16884K	Nov 2002	1.0%
MIL-DTL-16884L	Oct 2006	0.5%
MIL-DTL-16884M	Aug 2012	0.1%

6.3 Alternative Fuels

There is some consideration of alternatives to liquid fossil oil fuels for the marine industry. Three of these are biodiesel, Liquefied Natural Gas and Methanol – Dimethyl Ether.

6.3.1 Biodiesel

An extensive review across many transportation sectors of the emissions of biodiesel compared to conventional low sulphur diesel, shows overwhelming evidence for a 50-90% reduction in Particulate Matter (PM) emissions. This is due to the lower concentrations of aromatic hydrocarbons, higher cetane numbers and higher oxygen content in biodiesel. Mixtures of biodiesel and conventional diesel show progressively decreasing PM emissions as biodiesel content increases. For example, 20% biodiesel mixtures reduced PM emissions by ~20 -30%, while 100% biodiesel reduced PM emissions by 50-70% compared to low sulphur diesel [6]. Emissions from the combustion of low sulphur diesel are predominantly comprised of Black Carbon (BC) and organic matter, so the quoted PM reductions are likely proxies for BC. Biodiesel contains 8 – 11% less energy than conventional diesel and fuel consumption will therefore increase by this amount. A main driver for biofuels is the reduction in life cycle carbon

(CO₂) and it has been suggested that the increased fuel consumption (and CO₂ emissions) from biodiesel are significantly offset by the closed carbon cycle of biodiesel feedstock [6].

Within the shipping industry a number of biofuel experiments have taken place. Jayaram et al [38] showed a 38% reduction in BC using 50% biodiesel/ultra-low sulphur diesel mixture, while Petzold et al [39] showed BC reductions in the range of 60 – 75% for four different biodiesels compared to HFO. The biodiesels used in the studies referenced were sourced from vegetable oil (soya, palm, sunflower) or animal fats.

6.3.2 Liquefied Natural Gas (LNG)

LNG is natural gas which has been cleaned and cooled to -162°C, at which temperature it is liquid at atmospheric pressure. The liquid fuel is reduced in volume by a factor of 600%, which allows feasible energy storage density for fuelling ships: LNG has about 85% of the energy stored per unit volume compared to conventional liquid fuel. Compared to Intermediate Fuel Oil, LNG is very clean burning: it emits 23% less CO₂, 80% less NO_x and 92% less SO_x.

Extensive reviews of the effect of Liquefied Natural Gas (LNG) on PM emissions within light-duty (passenger cars) and heavy duty diesel engines (buses, trucks) also suggest that PM emissions are cut by 88 – 99% [6]. Because the majority of PM emissions from ultra-low sulphur diesel (ULSD) fuel are BC, these PM reductions are likely an effective proxy for BC. US EPA data suggest that BC and PM emissions are substantially reduced when using LNG [40]. Some fugitive emissions of methane during LNG production and combustion (methane slip) partially offset the otherwise positive emissions reduction from use of LNG.

6.3.3 Methanol – Dimethyl Ether (DME) (Ethanol – Diethyl Ether)

DME is the product of the dehydration of methanol, which has a higher cetane number than methanol itself. It can be produced from many sources, i.e. coal, biomass and CO₂. The use of DME directly as a fuel in diesel engines, or the onboard dehydration of methanol to form DME, is the subject of significant research in the assessment of the “well to wheels” potential as an alternative to HFO. According to the study for IMO [41], the SPIRETH program (Alcohol (spirits) and ethers as marine fuel) investigates the onboard catalyzed dehydration of methanol or ethanol. Limited data on this fuel source suggests that a 97% drop in particle number results from the use of dehydrated ethanol compared to a diesel engine (presumably running ultra-low sulphur diesel). The SPIRETH report and a report from Wärtsilä suggest that the use of DME produces “no particulate emissions” or “low or no soot”. On other parameters there appeared to be a 9% reduction in fuel efficiency and a 35% reduction in NO_x emissions, although these were based on one series of measurements.

Methanol storage is reported to have similar storage requirements as LNG while DME can be integrated into LNG fuel and engine systems. It should be noted that the process to extract DME from fossil feedstock is energy intensive and the net environmental benefit is thereby reduced. Production of DME from renewable sources or as by-product from other productions is also showing promise with net CO₂ reductions of 95% when produced from biomass.

7 Conclusions

The body of work on technologies to reduce marine diesel emissions is substantial, and solutions are reaching the commercial marketplace.

Internal engine modifications to reduce NO_x are largely mature and are present in most new engines. Such modifications appear to have reached the limit of what can be expected in terms of NO_x reduction and need to be supplemented by external pre- and post-combustion systems to achieve the performance set by upcoming tighter NO_x (Tier 3) limits. Although development work continues on various pre-combustion NO_x reduction technologies (mainly aimed to reduce combustion temperatures by, for instance, water injection), the more mature technologies are post-combustion, particularly selective catalytic reduction.

Tighter SO_x emission requirements are leading to sales of post-combustion gas cleaning systems as an alternative to use of (expensive) low sulphur fuel.

Although one post-combustion technology (Ecospec's CSNOx) has demonstrated reduction of CO_2 emissions as well as NO_x and SO_x reduction, it remains to be seen if effective commercial scale CO_2 reduction is feasible.

Particulate filters have been demonstrated as effective in reducing Particulate Matter and Black Carbon emissions when lighter fuels are burned.

For naval application, which comprises high or medium speed engines running on very low sulphur fuel, lower emission routes are most likely:

- To achieve Tier III NO_x , implement diesel engine internal improvements supplemented by selective catalytic reduction. The major downside is the need to carry urea in proportion to the fuel carried. Plasma technologies may be an alternative for the future.

- No change to SO_x and PM/BC emissions by naval vessels since they are already low due to the high specification of the NATO standard fuel.

A summary of marine diesel air emission reduction technologies, their effectiveness, technological maturity and applicability to the Canadian naval vessels is presented in Table 3.

Table 3: Diesel Emission Reduction Technologies - Summary

TECHNOLOGY	POLLUTANT REDUCTION EFFECTIVENESS							COMMENTS	TRL	APPLICABLE TO RCN?
	CO ₂	CO	SO _x	NO _x	HC	PM	BC			
Basic IEM:		possible						New engines and retrofit technology for		No - Slow speed
Low NOx Slide Valve	–	increase	–	10%-30%	30%	25% - 50%	25% - 50%	slow-speed 2-stroke engines only.	9	not used by RCN
Advanced IEM / combination	–	–	–	30% - 40%	–	probably reduced	–	Usually used as combination of various technologies	9	Yes - appearing in Tier III NOx engines
Humid Air Motor (HAM)	increased (power used)	–	–	20%-80%	–	–	0% - 50%	Tested onboard; actual implementation very limited	7	possible
Selective Catalytic Reduction (SCR)	–	–	–	90% - 92%	–	25% - 40%	–	Expected to be commercially available in 2014	9	yes
Selective Non-Catalytic Reduction (NSCR)	–	–	–	50%	–	–	–	Extensive modification of engine required; ammonia slip possible	6	possible
Scrubbers	increased (power used)	–	90%	–	–	–	–	bulky, most applicable to heavier fuels	9	no
CSNOx	77%	–	99%	66%	–	–	–	Initial performance claims are very promising. Watch for implementation success.	7	possible
Water in Fuel Emulsion (WIFE)	increased (power used)			30% - 60%		60% - 90%	45% - 50%	Can lead to visible exhaust plume.	8	likely not
Exhaust Gas Recirculation (EGR)	–	possible increase	–	20%-90%	–	possible increase	0% - 20%	Accumulation of PM (soot) from recirculated gases in the EGR system affects its efficiency. May require scrubber also.	8	likely not
Combustion Air Saturation System (CASS)	increased (power used)			30%-60%				No commercial application yet	6	likely not
Diesel Particulate Filter (DPF)	increased (back-pressure)	–	–	–	–	55% - 95%	70% - 99%	Effective on diesel with <0.05% sulphur.	7	possible
Plasma Reduction System	increased (power used)			97%		90%		Increase fuel consumption thus CO ₂ emissions.	6	possible
								Can be used alone or with SCR/NSCR		

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List of symbols/abbreviations/acronyms/initialisms

ABS	American Bureau of Shipping
AWPPR	Arctic Waters Pollution Prevention Regulations
ASPPR	Arctic Shipping Pollution Prevention Regulations
AWPPA	Arctic Waters Pollution Prevention Act
BC	Black Carbon
CASS	Combustion Air Saturation System
CO	Carbon Monoxide
CO ₂	Carbon Dioxide
dBC(A)	Decibel (C-scale weighted)
DME	Dimethyl Ether
DND	Department of National Defence
DPF	Diesel Particulate Filters
DRDC	Defence Research & Development Canada
DRDKIM	Director Research and Development Knowledge and Information Management
ECA	Emission Control Area
EGR	Exhaust Gas Recirculation
GHG	Greenhouse Gas
HAM	Humid Air Motor
HC	Hydrocarbon
HFO	Heavy Fuel Oil
IEM	Internal Engine Modifications
IFO	Intermediate Fuel Oil
IMO	International Maritime Organization
IPCC	Intergovernmental Panel on Climate Change
JSS	Joint Support Ship
LNG	Liquefied Natural Gas
MARPOL	International Convention for the Prevention of Pollution from Ships
MEPC	Marine Environment Protection Committee
MDO	Marine Diesel Oil

NATO	North Atlantic Treaty Organization
NMVOCs	Non-methane Volatile Organic Compounds
NO _x	Oxides of Nitrogen
NTP	Non-Thermal Plasma
PACR	Plasma Assisted Catalytic Reduction
PM	Particulate Matter
R&D	Research & Development
RCN	Royal Canadian Navy
SCR	Selective Catalytic Reduction
SNCR	Selective Non-Catalytic Reduction
SO _x	Sulphurous Oxides
SPIRETH	Alcohol (spirits) and ethers as marine fuel (pilot DME project)
TC	Transport Canada
TRL	Technology Readiness Level
ULSD	Ultra-Low Sulphur Diesel
WiFE	Water in Fuel Injection

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