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CURRENT STATE AND DEVELOPMENT TRENDS IN THE FIELD OF LARGE DIESEL AND GAS ENGINES

Dobrivoje Ninković [1]

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RESEARCH ARTICLE

ABSTRACT: Large Diesel and gas engines with power higher than approximately 1 MW play a major role in the sea and land transport of people and goods, but also in the production of electrical energy in remote areas, for peak load balancing, and backup systems. While their total installed power and fuel consumption are vastly smaller than with their road transport counterparts, the vehicles they propel (ships and trains) represent the most efficient freight transport modes in existence. It is thus their importance for the world economy that has been driving their development, resulting in these engines belonging to the group of the most efficient thermal machines available to the mankind.

Presented in the paper is a survey of the current development state of the large Diesel and gas engines in terms of their thermodynamic performance, emission levels and the means for achieving them, and fuels used. Due to its indispensability for achieving the high performance of these engines, turbocharging is given a particular treatment in the paper.

Based on the study of the contemporary literature, an attempt is made to identify main development trends in this area. With regard to the latter, special attention is devoted to the so-called dual-fuel engines (Diesel and gas), which appear to have enjoyed a rapid development in the last decade.

KEY WORDS: large engines, diesel engines, gas engines, dual-fuel engines

[1] *Dobrivoje Ninković, PhD., Ruchwiesenstr, 28, 8404 Winterthur, Switzerland., dninkovic@bluewin.chk (*Corresponding author)*

TEKUĆE STANJE I TRENDOVI RAZVOJA U OBLASTI VELIKIH DIZEL I GASNIH MOTORA

REZIME: Veliki dizel i gasni motori sa snagom većom od oko 1MW, imaju glavnu ulogu u pomorskom i kopnenom transportu ljudi i robe, ali i u proizvodnji električne energije u udaljenim područjima, za prihvatanje vršnog opterećenja i rezervne sisteme. Dok su njihova ukupna instalisana snaga i potrošnja goriva znatno niže nego kod motora u drumskom saobraćaju, vozila koja oni pokreću (brodovi i vozovi) predstavljaju najefikasnije vidove transporta tereta koji postoje. Zbog toga je njihov značaj za svetsku ekonomiju pokretač njihovog razvoja, što je dovelo do toga da ovi motori pripadaju grupi najefikasnijih toplotnih mašina dostupnih čovečanstvu.

U radu je prikazan pregled trenutnog stanja razvoja velikih dizel i gasnih motora sa stanovišta njihovih termodinamičkih performansi, nivoa emisije i načina za njihovo postizanje i goriva koja koriste. Zbog zahteva za postizanje visokih performansi ovih motora, posebna pažnja, u ovom radu, je posvećena turbo punjenju. Na osnovu proučavanja savremene literature učinjen je pokušaj da se identifikuju glavni trendovi razvoja u ovoj oblasti. Stoga, posebna pažnja je posvećena tzv. dvogorvim motorima (dizel i gas) za koje se čini da se u poslednjoj deceniji doživeli nagli razvoj.

KLJUČNE REČI: veliki motori, dizel motori, gasni motori, dvogorivi motori

CURRENT STATE AND DEVELOPMENT TRENDS IN THE FIELD OF LARGE DIESEL AND GAS ENGINES

Dobrivoje Ninković

1. INTRODUCTION

The year 2017 marked the 125th anniversary of the Rudolf Diesel's patent on the theory and the realisation method for combustion engines (in original: "Arbeitsverfahren und Ausführungsart für Verbrennungskraftmaschinen"), a patent formulated rather broadly, but which in essence dealt with an engine with constant temperature and slow combustion. The thermodynamic goals that Diesel set for his engine concept in 1892 were bold, but at the same time held a powerful prophecy for the future: maximum cylinder pressure of 253 bar and an efficiency of 58%; and that at the time when the dominating prime mover – the steam engine – ran with an efficiency of mere 7%.

The patent brought neither a fortune nor a personal happiness to his inventor, but it can be seen as the starting point for the rise of an engine branch without which the modern large-scale goods and passenger transport would have been unthinkable, namely the large engine division. It definitely took time for this engine branch to set foot and gain momentum, for it wasn't until 1912 that a four-stroke Diesel engine was used as the main propulsion set on a high-sea ship, the MV Selandia [1]. However, it was not a sign of change in the sea transport, for in the Second World War two thirds of the shipping was still driven by steam, and there were only two capital warships powered exclusively by Diesel engines. The situation started to change with the first application of the turbocharging to a two-stroke Diesel engine in 1946 [2], partly due to the "downsizing" of this engine kind brought about by the turbocharging, for turbocharged four-stroke engines were in use on ships since 1927.

It is now a recognized fact that shipping is the most efficient form of bulk transport, without which the globalization of the world trade would hardly have been possible. Given that the carrying capacity of modern container ships already exceeds 21000 TEU (Twenty-foot Equivalent Units) containers, and that they are almost invariably propelled by a single low-speed two-stroke engine (75570 kW in the case of OOCL Hong Kong, currently the world's largest container ship), the importance of the large engines can hardly be overstated.

The breakthrough in rail transport came about in 1939 with the introduction of the EMD FT, the two-stroke Diesel-electric locomotive in the U.S.A. [3]. The Second World War slowed the proliferation of the Diesel engine in this transport sector too, because it was forbidden to build Diesel engines in the war-time U.S.A. on account of the steam engine being much better known and requiring less precious materials in the production. Diesel engines have also been widely used to generate electricity, an example of which is the Diesel locomotive whereby the engine is used to generate electricity to be supplied to the electric motors driving the wheels. On ships, Diesel generators are used to supply electricity for lighting, ventilation, powering the ballast water pumps for balancing the ship, but also for auxiliary propellers, i.e. thrusters, used for enhancing the ship's manoeuvrability, especially in ports.

Another important application field of large engines is the stationary electricity generation, either as the so-called "island solutions" in areas without connection to an electric grid system, or for supporting a national grid system at meeting the peak or a sudden load demand. A typical power plant of this kind may consist of one to twenty 10 to 20 megawatt units ready to start at short notice, which is of an ever increasing value in connection with the often unpredictable availability of the renewable electrical energy sources, such as e.g.

the wind turbines [13]. Lest the impression be given here that the Diesel engines are the only large engines in existence, the gas-burning engines actually predate the Diesel ones by some 30 years, as gas was available for lighting, and thus the so-called atmospheric gas engines appeared. However these engines were very inefficient and the development impetus for gas engines came about with the four-stroke patent of Otto in 1876.

Large gas engines experienced an ever accelerating development rate in the last 20 to 30 years, constituting nowadays a mature segment of the large engine family. At powers of up to 50 MW, low-speed, two-stroke gas engines are more efficient than the corresponding gas turbines; and their small environmental impact makes them also attractive for being used as prime movers in the transportation as well, competing ever more with the four- and two-stroke Diesel engines on ships. As a matter of fact, the former clearly-cut difference between the gas and Diesel engines has been progressively blurring in the past decade or so due to the introduction of the dual-fuel engines that are capable of burning both fuels, switching between them according to the situation at hand.

Given that the slow-running two-stroke Diesel engines are at least equal if not better in terms of the fuel efficiency than the gas turbine installations, being thus the most efficient thermal machines known to man, and the importance of the large engines in general to the large-scale transportation of goods and people, it is of interest to review their current state and development trends, borrowing thus the motto "Quo Vadis Large Engines" from a recent Guest Commentary in MTZ Industrial [4].

2. MAIN ENGINE TECHNOLOGY DRIVERS

The engine technology has in the past been driven by the need to continuously fulfill the standard criteria of the general product development, namely:

- Efficiency, i.e. the operating costs
- Price, i.e. the production price at the manufacturer's side, and the purchase price at the buyer's side
- Reliability and safety
- Ease of maintenance (also a part of the operating costs).

The state and its agencies may have intervened insofar as to define regulations concerning the reliability and safety of the products, which has traditionally been the concern of the insurance business as well, leaving the rest to the negotiations between the manufacturers and buyers.

The situation changed sharply as the concern arose for the environment pollution and its consequences upon the human and animal health, which in the case of large ship engines may be dated to the year 1997 as the IMO (International Maritime Organization) published the MARPOL (Maritime Pollution) Annex VI [5]. This agreement was intended to come into effects on 1.1.2000, subject to being ratified by enough countries to reach 50% of the world ship tonnage. There were several previous declarations to the subject of the environment protection, but it was the first time that concrete emission values were to be applied along with the measures and the timetable for their implementation and enforcement. A process was thus set up that would become a major development driver in the engine business for the decades to come, as the regulations were to be updated, i.e. become ever stricter, on a regular basis [18].

The evolution of the IMO limits on the nitric oxides (NOx) emissions from large engines is presented in Figure 1 below [6]. It is valid for marine Diesel engines with power larger than

130 kW, but not for vessels operating in national waters, where local legislation applies. It is seen that the limits were lowered in stages (so-called Tiers), first mildly, and then drastically in the so-called Emission Control Areas (ECA). These are to be defined by the individual countries. It is also apprent that the slow-running engines (< 250 rpm) were allowed higher NOx values in the beginning, but the Tier III practically eliminated the difference between the two- and four-stroke machines.

The sulphur limits were also scheduled to be reduced with time at the global and ECA levels, but since the SOx emissions are primarily determined by the sulphur content in the fuel, they have repercussions upon the engine only insofar as regards the exhaust after-treatment. The soot (black carbon) and particle emissions are currently not regulated, and it is apparently not likely that the discussions within the IMO are to be soon concluded.

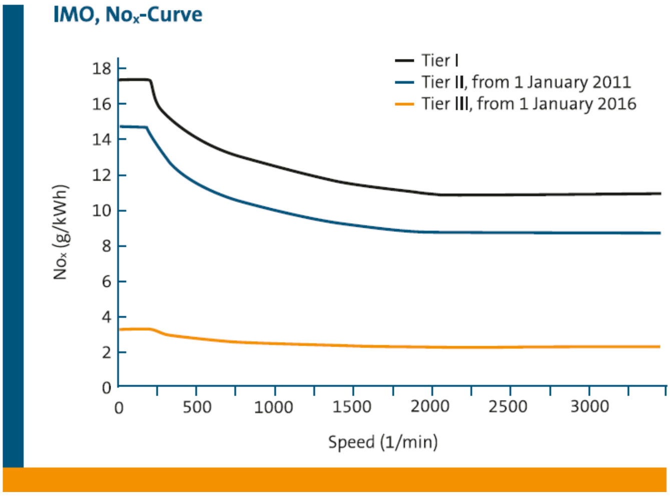

Figure 1. Evolution of the No_x legislation for large maritime engines

The emission limits for rail engines came about at approximately the same time, in the form of the EU Directive 97/68/EC, which was adopted by the Int. Union of Railways (UIC) as the Code 624V, shown in Figure 2 below. The former was superseded in 2016 by the all-encompassing NRMM (Non-Road Mobile Machinery) legislation (EU 2016/1628), which covers practically everything from the small agricultural machinery to the inland waterway vessels and electricity generating sets [7]. The relevant emission limits for the rail transport are shown in Figure 3 below.

Stage	Power, Speed	NO_x [g/kWh]	HC [g/kWh]	CO [g/kWh]	PM [g/kWh]	Date
UIC II	$P_n \leq 560$ kW	6.0	0.6	2.5	0.25	1 Jan 2003
	$P_n > 560$ kW $n_n > 1000$ rpm	9.5	0.8	3.0	0.25	1 Jan 2003
	$P_n > 560$ kW $n_n \leq 1000$ rpm	9.9	0.8	3.0	0.25	1 Jan 2003

Figure 2. The UIC Code 624V emission legislation for railway propulsion engines

Similar legislation for the rail transport exists in other countries, with the U.S.A. NOx limits of 1.74 g/kWh for their Tier 4 (2015+) locomotive engines being more stringent than the Stage V (2021+) EU limits of 4 g/kWh [6].

The above mentioned exhaust gas limits must be met without sacrificing the fuel efficiency. However, the latter determines the CO2 emissions; and as a Greenhouse Gas (GHG), CO2 is also the subject of regulatory measures. Although the global shipping is currently responsible for only 2.5% of the worldwide CO2 emissions [9], IMO has initiated a program for reducing the total annual GHG emissions by 50% relative to the 2008 level, i.e. the CO2 emissions by 40% by the year 2030. To this end, IMO has introduced mandatory technical (EEDI) and operational (SEEMP) measures for the energy efficiency of ships [10].

The term EEDI (Energy Efficiency Design Index) is a comprehensive efficiency parameter that takes into account not only the main engine efficiency, but also all other GHG emissions, the ship's capacity, the so-called „hotel load“ (crew facilities), and speed. Referring to Figure 4 below, there is a reference EEDI line for each ship commissioned after January 1st of 2013 as a function of its DWT (Deadweight Tonnage), and a set of required lines for the new or retrofitted ship generations as a parameter, reducing by 10% every five years [9].

Locomotive propulsion engines

Stage	Power Cylinder displ.	NO_x [g/kWh]	HC [g/kWh]	CO [g/kWh]	PM [g/kWh]	PN [#/kWh]	Date[A]
		HC + NO_x [g/kWh]					
III A	$130 \le P_n \le 560$ kW	4.0		3.5	0.2	–	2007
	$P_n > 560$ kW	6.0	0.5	3.5	0.2	–	2009
	$P_n > 2000$ kW $V_{h,z} > 5$ L	7.4	0.4	3.5	0.2	–	2009
III B	$P_n > 130$ kW	4.0		3.5	0.025	–	2012
V	$P_n > 0$ kW	4.00[B]		3.50	0.025	–	2021

[A] Date for placing on the market of engines, type approval one year earlier.
[B] A = 6.00 for gas engines.

Railcar propulsion engines

Stage	Power	NO_x [g/kWh]	HC [g/kWh]	CO [g/kWh]	PM [g/kWh]	PN [#/kWh]	Date[A]
		HC + NO_x [g/kWh]					
III A	$P_n > 130$ kW	4.0		3.5	0.20	–	2006
III B	$P_n > 130$ kW	2.0	0.19	3.5	0.025	–	2012
V	$P_n > 0$ kW	2.00	0.19[A]	3.50	0.015	$1{*}10^{12}$	2021

[A] Date for placing on the market of engines, type approval one year earlier.
[B] A = 6.00 for gas engines.

Figure 3. The EU 2016/1628 emission legislation for railway propulsion engines

Ship owners can improve the respective EEDI figures of their ships by various measures, such as making changes to the engine (installing better injectors, turbochargers, etc.), and by optimizing the entire energy flow of the vessel. Engine manufacturers are thus stimulated not only to improve their products, but also to offer various devices for enhancing the performance of the existing engines in service.

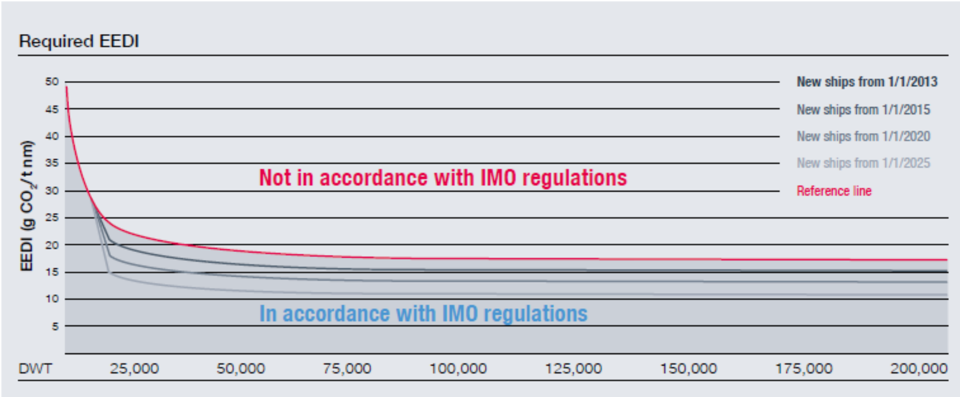

Figure 4. The required IMO EEDI lines for the existing and future ships [8]

As regards meeting the above goals set by the respective legislation bodies, Schlemmer-Kelling [5] writes that the potential for increasing the efficiency at high engine loads by improving the combustion process, the gas exchange, and the mechanical efficiency has already been exhausted. The only remaining measures would be increasing the firing pressure, and opting for a two-stage turbocharging with an intercooler. In his opinion, it is the part-load where larger potential for improvement exists in terms of better air supply to the cylinders, and optimized fuel injection.

It is at this place necessary to mention one technology that has been and remains instrumental to achieving the improvements required for meeting the exhaust legislation, namely the supercharging, which in a vast majority of cases is realized by means of turbochargers. There is now hardly a large engine without turbocharging, and new theoretical IC cycle variants such as Miller and Atkinson would have been impossible to realize without this technology. It has been developing in parallel with the engines, exchanging the development incentives in both directions. This is also true of the newest T/C products, namely the two-stage turbochargers that have been offered as mature products by all major T/C manufacturers in the last years, e.g. [11][12]. The fact that the GHG emissions from many energy sectors in Europe have been falling, and those from transport have increased over the last decades, and are expected to increase significantly to 2050 [14], has become an additional technology driver in the large engine sector. The GHG emissions of fuels with a smaller carbon content than the standard marine fuel oil (MFO) and the heavy fuel oil (HFO), such as .e.g. the Liquid Natural Gas (LNG), have a favourable impact on the emissions [15], and the use of LNG is thus expected to rise [16], but presupposes the availability of the corresponding engines [17].

3. SLOW-RUNNING TWO-STROKE ENGINES

3.1 Current development state

The two-stroke, low-speed large engine industry has undergone a concentration process, with the result that there are now only two major companies developing but not necessarily manufacturing the largest engines, these being MAN Energy Solutions (formerly MAN Diesel & Turbo) of Augsburg, Germany, and a company now called WinGD (Winterthur Gas & Diesel), which started in 2015 as a joint venture of Wärtsilä of Finland with the China State Shipbuilding Corporation (CSSC), but is from 2016 owned solely by CSSC.

The business model of both companies consists of developing state-of-the-art Diesel engines, which are then built in license almost exclusively in the Far East. MAN also manufactures turbochargers, whereas WinGD do not, relying mostly on ABB Turbo Systems as the turbocharger supplier. The most powerful engines of both companies are in the same range (Wärtsilä: 80 MW, MAN: 87 MW), with Wärtsilä having the largest one in use with the power of 80080 kW on board the container ship Emma Maersk.

Kobe Diesel, having recently acquired the large engine program of Mitsubishi Heavy Industries (MHI), is the third company developing and manufacturing this class of engines (about 2% of the world market), their range currently extending up to about 35 MW units.

Before the financial crisis of 2008, the container ships were built for speed, and it was expected that the future ship classes with the carrying capacity of the order of 20000 TEU would need main propulsion power of over 100 MW. However, this trend has not materialized because the shipping companies realized that significant fuel savings are possible by reducing the cruising speed somewhat. For example, reducing the ship speed from 27 to 22 knots, i.e. by 19%, lowers the nominal engine power to 42%, saving thus 58% of the hourly fuel consumption [19]. So now the 21000 TEU OOCL Hong Kong with the main propulsion power of 75 MW has a smaller engine than the 16000 TEU Emma Maersk.

Main characteristics of modern two-stroke, main propulsion ship Diesel engines are:

- Long-stroke crosshead design
- Cylinder diameter of up to about 100 cm, stroke-to-bore ratio about 4 and higher (in newer engines)
- Hydraulically activated exhaust valve in the cylinder cover, electronic valve control
- Single-stage turbocharging, mechanical blower for the low power regime
- Electronically controlled fuel injection, common rail (MAN and WinGD), mechanical (MHI)
- Up to three injection nozzles per cylinder in order to achieve fuel injection flexibility
- HFO and MFO as the main fuel types, switchable on demand.

Three general technology trends are discernible in the low-speed two-stroke large engine segment:

- Comprehensive engine optimization aimed at improving the fuel efficiency, reliability, maintainability, etc. achieving thus low life-cycle costs
- Changes with regard to meeting the emission legislation, esp. the current Tier III norm
- System optimization (ship, engine, propulsion, operating procedures) for improving the EEDI figure.

The above trends are not isolated from each other – they rather intersect and interact in the attempt to meet the changed economic criteria of the customers, namely the Total Cost of

Ownership (TCO) that now dominates the decision making process instead of the previously most important criterion of the First Cost, i.e. the purchase price.

Discussing the numerous measures and solutions that have been studied and realized in order to arrive at the current optimization level of this engine class is beyond the scope and limits of this paper. Therefore, only a short list will be given of the most important improvements and optimization areas [21], [22], [23], [24], [25]:

- Fuel injection: electronic control, common-rail in different variants, pumps and injectors
- Exhaust valve electronic control
- Auto-tuning in the engine control
- Mechanical improvements of the engine structure
- Minimization of the mechanical (friction) losses in the critical areas, e.g. in the cylinder ring packing and the crosshead guide shoe bearing
- Cylinder lubrication system
- Cylinder cooling
- Turbocharging, e.g. variable turbine area, turbocharger cut-out at low loads, etc.

As an example, shown in Figure 5 below is a diagram showing a possible fuel oil cost savings for a 1 g/kWh reduction of the lubrication oil consumption with optimized piston rings [25].

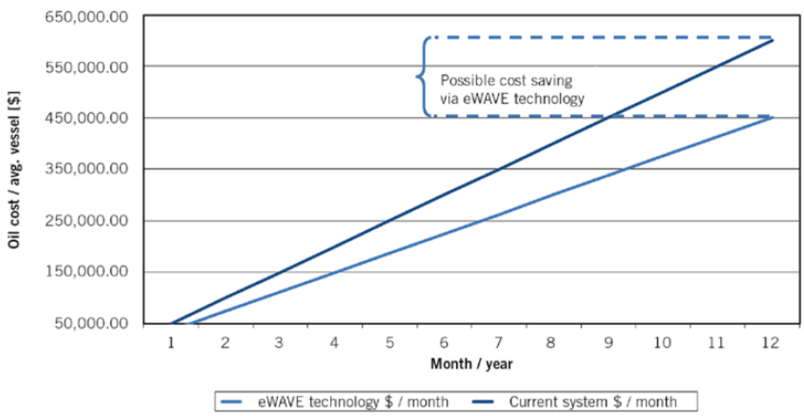

Figure 5. Possible savings by reducing the lubrication oil consumption by 1 g/kWh [25]

In looking at the optimization possibilities in the entire ship propulsion system, one of the obvious elements is the ship's propeller, and its feature of increasing the efficiency with the diameter. Using larger propellers necessitates lower engine rotation speeds, and in order to keep the engine power at the level required by the ship, the stroke-to-bore (S/B) ratio must be increased. This was the approach that led MAN to develop the G-Type engine, with S/B ratio of up to five [20]. According to MAN, CO2 reductions of up to 7% are possible as a part of the propulsion package. Referring to Figure 6 below, overall efficiency increase of 4-5% should be possible with the new engine and a larger propeller.

With the introduction of the RT-flex mid-size engines (48 to 68 cm bore) in the mid-nineties, Wärtsilä also increased the S/B ratio to over 4.0, and this trend continued with the current Generation X-engines. The latter engines have an S/B ratio between 4.1 and 4.5, with the largest model W-X92 (92 cm bore) still at 3.8 for the lack of manufacturing capacity at the crankshaft factory [21]. The authors point out the compromises that need to be made when realizing the long-stroke engines, both from the standpoints of the manufacturing, and of the engine room limitations on the ship.

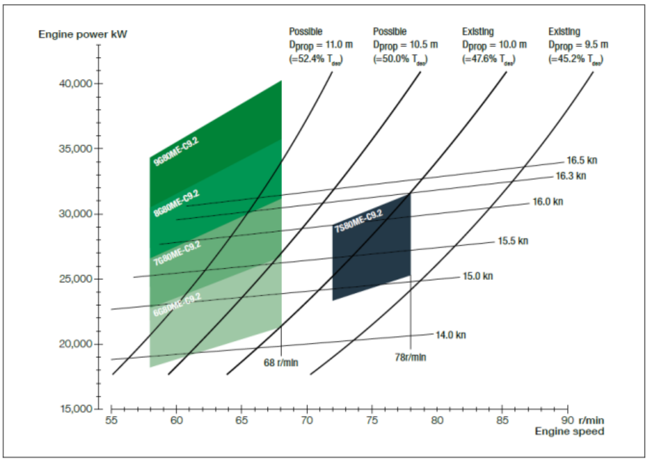

Figure 6. Efficiency gain by using a larger propeller with a G-Type engine [20]

As regards meeting the emission legislation, particularly the NOx pollution, already at the introduction of the Tier II norm the engine designers were confronted with the so-called "Diesel dilemma". This refers to the fact that there is no simple way towards simultaneously lowering the fuel consumption and reducing the emissions, for the mechanisms of their generation within the cylinder are different and lead in part to opposite effects. Referring to Figure 7 below, reducing the NOx emissions is accompanied by a fuel consumption increase, which MAN in 2010 quantified to 6 g/kWh for their mechanically controlled engines, and 4 g/kWh for the electronically controlled ones [26].

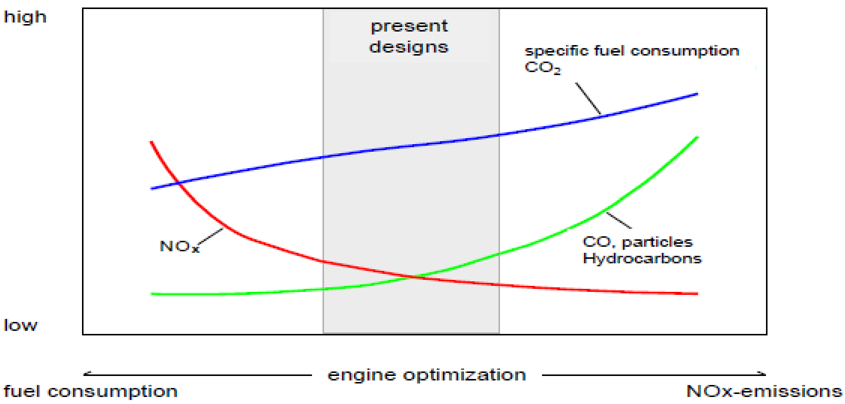

Figure 7. The "Diesel dilemma" [18]

MAN subsequently reduced the fuel consumption penalty for their Tier II engines to 1-2 g/kWh by a combination of measures [26]:

- increased scavenging air pressure
- reduced compression ratio (two-stroke Miller timing)
- increased maximum combustion pressure
- adjustments of the compression volume, and other engine design changes.

Wärtsilä introduced a new generation of two-stroke, Tier II conformable Diesel engines in 2011 [22]. Beside the already quoted optimization measures, the new RT-flex engines featured full electronic control of the exhaust valves and the common-rail injection. As mentioned above, these engines are now offered by WinGD.

Compliance with the Tier II limits adds one more parameter to the procedure for matching the engine speed and power with the nominal operating point of the vessel's propeller. This means that there are limits to the lowest feasible BMEP (Brake Mean Eff. Pressure) level at lower engine ratings in the engine operation map, calling thus for stronger internal NOx reduction measures, which in turn may have adverse effects on the BSFC (Brake Specific Fuel Consumption). These measures include the reduction of the scavenging air pressure, use of extended "Miller timing" (late exhaust valve closure in conjunction with increased scavenge pressure), and reduction of the peak cylinder pressure – the ultimate measure because of its adverse effects on BSFC. The availability of electronic controls on the engine greatly facilitates the application of these measures to the engine [27].

Today, all commercially available low-speed two-stroke engines comply with the IMO Tier II legislation without any additional measures to the ones mentioned previously. Reducing the NOx emissions by additional 75% for compliance with the Tier III values stipulated for the ECA requires much more complex technologies [27], most of which are accompanied by considerable financial expenditures. Since the HFO remains the principal fuel in this field [5] and its high sulphur content will be tolerated only until 2020 (<5000 ppm in non-ECA afterwards), and that because of the high capital costs the oil refineries are unlikely to modernize their HFO plants for lower sulphur content, it is the engine manufacturers who will have to solve the SOx emission problem.

Several technologies for meeting the Tier III criteria have been already investigated and experimentally tested, and some of them have been also commercially available for a number of years, e.g. [28]:

- Selective Catalytic Reactor (SCR) with urea injection for reducing the NOx content; injection of ammonia gas (NH3) has been introduced as an alternative recently
- Exhaust gas scrubbing and/or washing in order to reduce the SOx content
- Dual-fuel engines (HFO at high sea, gas in the ECA)
- EGR (Exhaust Gas Recirculation).

Starting with the SCR technology, there has been experience with it on the low-speed two-stroke engines previous to the establishment of the IMO Tier II norm, but it was limited to stationary power plants, e.g. [28]. In this particular case, the engine manufacturer (MAN) quotes both the power plants equipped originally with the exhaust gas treatment, and the retrofitted ones. Given the power range of the plants mentioned (40 to 50 MW), the SCR and the auxiliary equipment may be quite large. While in these cases there was enough space to accommodate whatever equipment was necessary, an application of this technology on ships is confronted with a number of restricting factors. Retrofitting an existing ship engine must take into account factors like tight space in the engine room, ship balance, engine room deformation with various cargo arrangements, having enough space for routine engine maintenance, possibilities for a relocation of the existing auxiliary components of the engine, etc. [29].

Referring to Figure 8 below left, the SCR from the reference above is seen at the RHS of the engine. While this installation is not a true retrofit (the system was previously tested on the test-bed) and the engine room was redesigned to accept thus modified engine, it conveys the idea of the space requirements. The RHS picture shows a different SCR arrangement on an engine of comparable size to the previous one [30].

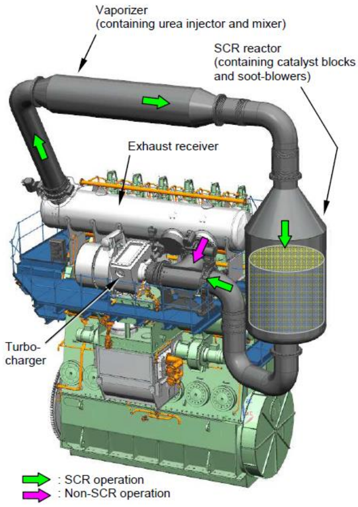

Figure 8. The SCR systems on two similar, middle-power two-stroke engines [29],[30]

Being installed between the exhaust receiver and the T/C turbine inlet, the SCR solutions shown above operate at high exhaust pressure and temperature. However, in both cases there is a single turbocharger on the engine, which greatly facilitates adding the SCR, but limits the solution to relatively low power engines. Large engines have typically several turbochargers, typically one for each three to four cylinders, and it is questionable whether this concept is applicable to such engines without major modifications. An SCR system after the turbochargers, i.e. at the funnel inlet is a more attractive solution for the high-power engines, and one such system was recently developed and commercially produced [31].

Dual-fuel engines have experienced very intensive development in the last years on the account of being capable of full Tier III compliance without the need for the exhaust after-treatment measures. The approach consists of using the HFO on the high sea, and gas (typically LNG) in the ECA. The two fuels differ significantly, but the engine remains essentially a Diesel, with modifications for the gas combustion. Two concepts have been established, the low-pressure one by Wärtsilä [32] and the gas injection (GI) of MAN [33], recently extended to the liquid gas injection (LGI), methanol, and ethane gas, i.e. practically to all gas fuels [34]. A comparison of the two concepts is presented in [37].

Referring to Figure 9 below, shown at the left is the low-pressure dual-fuel engine concept of Wärtsilä in the gas fuel mode. The gas is injected at a low pressure (about 16 bar) in the middle of the compression stroke. The compressed air-gas mixture is ignited at the end of the compression stroke by injecting the pilot fuel oil (MDO) into the prechambers in the cylinder cover. The mixture has a high air excess ratio, creating thus the conditions for a lean combustion. However, since the air-gas mixture is compressed to a high pressure, there may be a tendency towards knocking combustion under certain conditions, so the engine must be monitored by the control system. In addition, the compressioin ratio of the engine is determined by the gas fuel operation, which means that the engine is derated in the Diesel fuel mode. The MAN dual-fuel engine is based on high pressure gas injection directly into the cylinder, and subsequent ignition of the mixture by a pilot fuel flame. The combustion process is the same as in the same engine operating with Diesel fuel injection, such that there is no knock limit, as well as no limit on the compression rate and BMEP. The engine thus achieves the same thermal efficiency as when operating with HFO or MDO. The fuel gas is supplied to the engine at a pressure between 200 and 315 bar [33]; the pressure is dependent upon the engine load. If the gas is available in the gaseous state, it is supplied by a suitable compressor, whereas LNG must be supplied by a cryogenic pump and a vaporiser (LNG is kept at -162 °C in the tank). Since the gas fuel is potentially explosive if it leaks and mixes with the surrounding air, proper high-pressure sealing of the gas system must be guaranteed at all times.

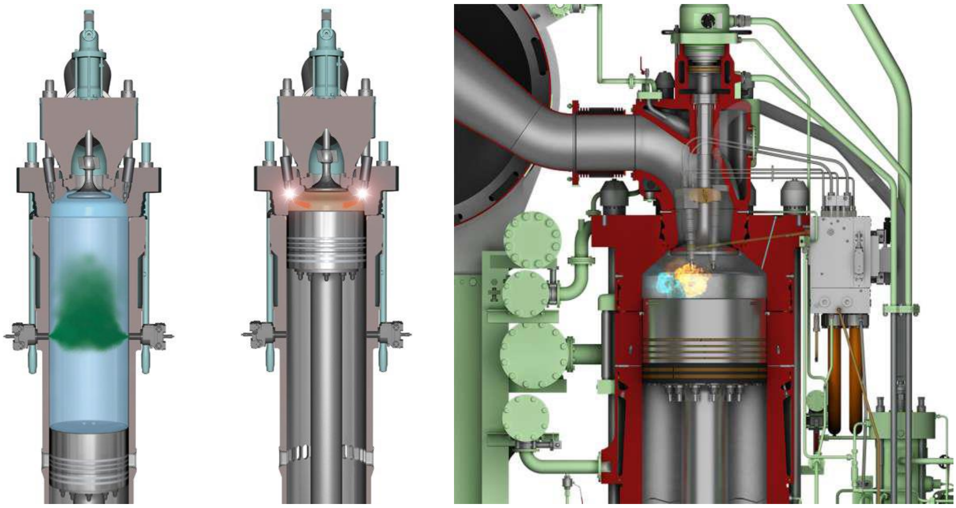

Figure 9. The Wärtsilä [32] and MAN [33]dual-fuel engine concepts

If a dual-fuel engine is for any reason not an attractive option for the ship owner, the Tier III limits can be met by burning MDO and employing the SCR and/or EGR for the exhaust gas treatment. The latter is only possible with very low sulphur content in the fuel oil, for sulphur is responsible for the major part of the PM (Particulate Matter) in the exhaust gas; alternatively, a SOx scrubber/washer can be used.

EGR solutions have been tested by MAN and their licensees, and found to meet the Tier III criteria. In comparison with the SCR, the necessary installation space is obviously much smaller (Figure 10), but the air supply to the engine, i.e. the turbocharging solution, must be redesigned [35], and a number of other non-trivial conditions met [36].

Figure 10. The MAN EGR concept (left) vs. the SCR solution for the same engine (right) [36]

3.2 Future R & D directions

According to the German engine consulting firm FEV, for price reasons the HFO remains the fuel of choice in the next decade, and this prediction has repercussions on the future research activities in the low-speed two-stroke engine field. While LNG is a very attractive fuel on an LNG tanker, using it as main fuel on an e.g. container ship is hardly a practicable idea, for LNG must be kept at -162 °C in the fuel tank and the inevitable boil-off must be continuously recompressed, which requires a special compressor. Therefore, there will be a legislation-driven need for attractive exhaust gas after-treatment solutions [5].

The other factor influencing the future research is expected to be the change to the TCO concept at the customer's side, which means that the engine is only a part of the much larger picture. However, since the TCO approach tends towards lower ship speeds, it leads sometimes to surprising results. Referring to Figure 11 below, a TCO-based optimal ship speed for a 1000 TEU container feeder would be 14 knots (prices as of 2015), roughly the value achieved by the sailing ships of the 19th century [37]. Because of the thus prolonged transport times, the ship operator will all the more be interested in having maximum efficiency of the entire business unit, including the engine.

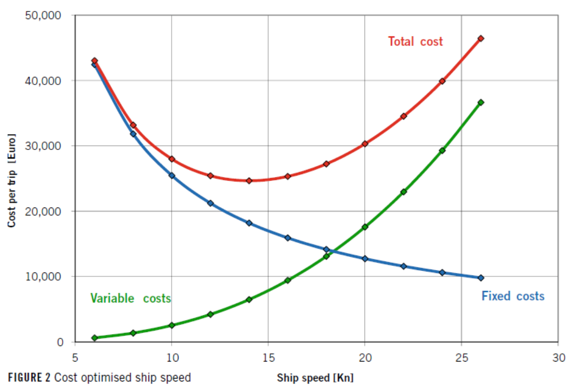

Figure 11. TCO-based optimal ship speed for a 1000 TEU container feeder [37]

The future development directions, as predicted by the FEV [5], are shown in Figure 12 below. Some of the solutions that should be important in the next decade are already available, such as common-rail injection, and the two-stage turbocharging [39]. The latter was tested a decade ago on an engine test bed and found unattractive, but should now become interesting on account of offering a possible 2 to 7 g/kWh reduction of the fuel combustion.

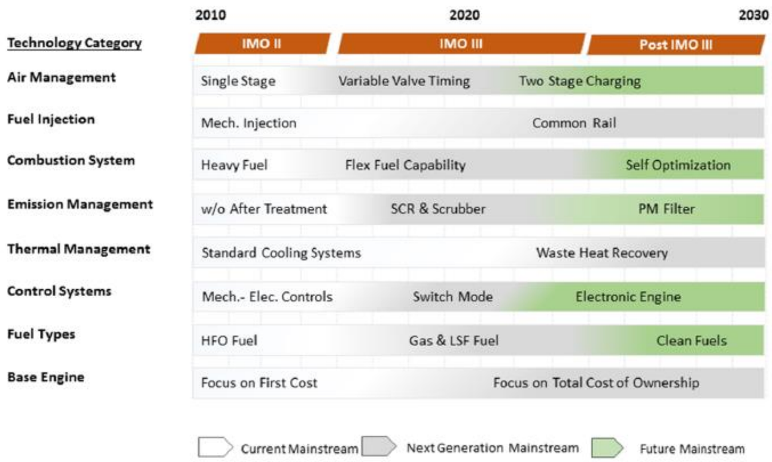

Figure 12. FEV road map for the necessary R & D activities in the two-stroke low-speed sector [5]

The above road map does not include a recent addition to the turbocharging technology that holds a considerable potential for a BSFC reduction in the slow-steaming ship mode, especially at the low end of the engine load (below 40%). It is based on adding an electric motor/generator (M/G) to the turbocharger, and in the solution of Mitsubishi [58] the electrical machine is an intrinsic part of the latter, sharing its shaft. Referring to Fig 13 (left) below, the M/G is located at the compressor inlet, in the middle of the filter/silencer. At high engine loads, the excess turbocharger power is used to drive the generator, reducing thus the demand on the main electricity generator; in a case reported in the paper, the generator consumed about 13% of the T/C turbine power [58].

At low engine loads, when the T/C turbine does not become enough energy in order to supply enough scavenging air to the engine, it is customary to use an electrically driven blower for this purpose. However, the electrical machine within the T/C can also be used in the motor mode, providing thus additional energy to the compressor, possibly obviating the need for the auxiliary blower. In the case reported in [59], generating the scavenging pressure by this method consumed 30% less electricity as compared to the auxiliary blower, reducing simultaneously the total fuel consumption by 1.3 to 6.7%, depending on the main engine operating point [58]. Obviously, this approach has a solid potential for the future, but the motor/generator price is currently rather high.

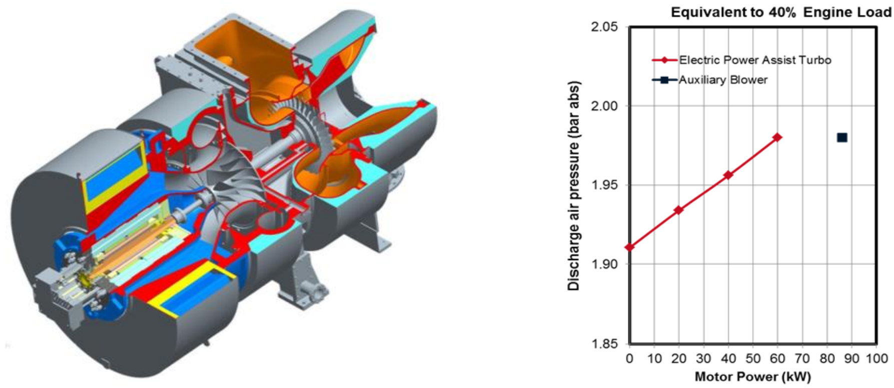

Figure 13. The "Electric-Assist" T/C of Mitsubishi [58], and the available scavenging pressure [59]

Regarding the EEDI as a technology driver, an interesting combination of the low-pressure EGR and the OCR (Organic Rankine Cycle) as a possibility for low-temperature waste heat recovery has recently been reported in the literature [60]. As a matter of fact, not only the EGR system can be used as the OCR heat source, but practically any low-temperature energy source can be harnessed for this purpose. Savings of the order of 6 to 7% can be expected from this heat recovery method.

4. FOUR-STROKE LARGE ENGINES

Traditionally, engines in this group are differentiated according to their speed (medium and high speed) and the fuel they burn (Diesel or gas). While the speed criterion is still valid (<1000 rpm: medium speed), the fuel criterion is not sharp anymore, for the proportion of dual-fuel engines appears to be rising in this segment too [40], [41].

With the exception of the air and road transports, large four-stroke engines are encountered on ships, boats, and submarines (main propulsion, auxiliaries), in the rail transport (locomotives and railcars), in the stationary power plants (electricity generation), on the oil drilling platforms, and in nonroad mobile machinery (excavators, etc.).

4.1 Current development state

The developments in this engine class have also been influenced by the exhaust gas legislation, especially in the maritime sector, but also by fuel price fluctuations and customer requirements. For example, a TCO projection for a 10 MW DF ship engine calculated in 2014 would give a three-year ROI (Return on Investment) for the gas operation, but due to the falling HFO prices, the same calculation made in 2016 would have incurred heavy losses [42]. This is where the flexibility of the DF engines could play a prominent role, provided that the vessel has provisions for storing both fuel types. Practically all modern ships with the four-stroke main propulsion are equipped with DF engines. Modern four-stroke engine portfolios are optimized to satisfy not only the exhaust gas norms, but also the ever-present striving towards maximum efficiency across the entire load range, low manufacturing costs, high reliability, and low maintenance costs. Treating an engine in the development process as a part of the entire object (ship, power plant, etc) requires solutions facilitating the system integration, both at the engine level itself, and at its „working place".

Turbocharging has apparently played a decisive role in bringing about both increased efficiencies and lowered emissions of polluting gases. The effects of higher charging pressure have been known for more than twenty years, but the impetus for developing such solutions came from the emission legislation, e.g. [43]. At the 2007 CIMAC Conference, Wärtsilä presented the first test-bed results for their Type 20 engine turbocharged with an ABB two-stage T/C delivering the air at a pressure ratio of 9.1, which enabled the use of the Miller timing [44]. Valuable results were obtained as regards the NOx reduction, and further research and development activities indicated. Theoretical studies of the Miller cycle indicate that the maximum cylinder pressure must not be increased in comparison with the Diesel cycle in order to obtain an efficiency gain [43]. Referring to Figure 14 below left, it is seen that the efficiency gain increases with the reduction in the maximum cylinder pressure, such that e.g. p_{max} of 190 bar with the Miller process results in the same efficiency as with the Diesel p_{max} of 270 bar, lowering the NOx generation at the same time. In making these calculations, it is important to use the ideal gas hypothesis (temperature-dependent specific heats), because the perfect gas hypothesis leads to incorrect results [43].

In order to achieve the above results, a large pressure drop over the engine is needed, calling thus for a turbocharging efficiency of about 70%, which in turn means a T/C compressor ratio of the order of ten (Figure 14, right). Such pressure ratios are impossible to realize with a single stage compressor if a useful performance map is to be simultaneously obtained, hence the reason for a two-stage compression. Together with the intercooling, which renders the overall compression process approximately isothermal, i.e. energy-efficient, favourable conditions are created for the realisation of the Miller process.

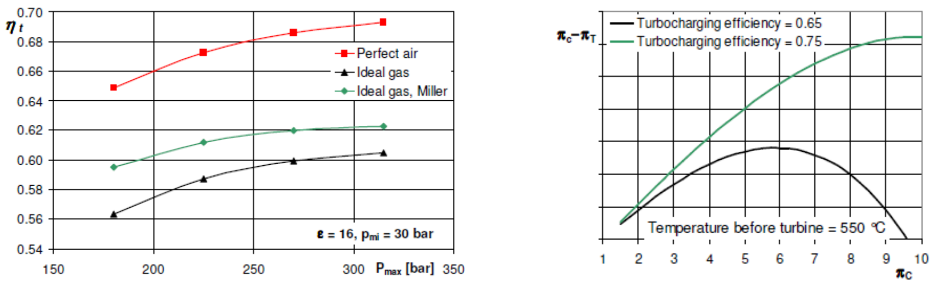

Figure 14. Theoretical Miller and Diesel efficiencies (left) and the required turbocharging efficiency (right) [43]

In 2015, Wärtsilä announced its "31" medium speed, four-stroke engine with the world's highest efficiency in its class (BSFC of 165 g/kWh with MDO), available in the Diesel, dual-fuel, and spark-ignited gas versions [45]. In the current Product Specification sheet (2017), the BSFC is quoted at 170 g/kWh for somewhat heavier distillates with the sulphur content of up to 2% [46]. An SCR is needed for compliance with the Tier III when operating with these fuel oils. In order to secure acceptable performance at part loads, the inlet valve drive has variable closure timing. The turbocharging technology has also made advances since the introduction of the first two-stage models. For example, the second generation of the two-stage turbochargers of ABB Turbo Systems (Baden, Switzerland) has a potential for achieving the equivalent turbocharging efficiency of up to 80% at overall pressure ratios of 12 [47], giving the engine designer possibilities for further performance improvements (Figure 15, left).

Looking at the low-pressure stage turbine efficiency of almost 90% (Figure 15, right, one has a feeling of the physical limits being about to be reached (turbine efficiency of over 90% has been attained on the test stand). Generally, the benefit of the two-stage turbocharging is a BSFC reduction of 3 to 5%, depending on the application [49].

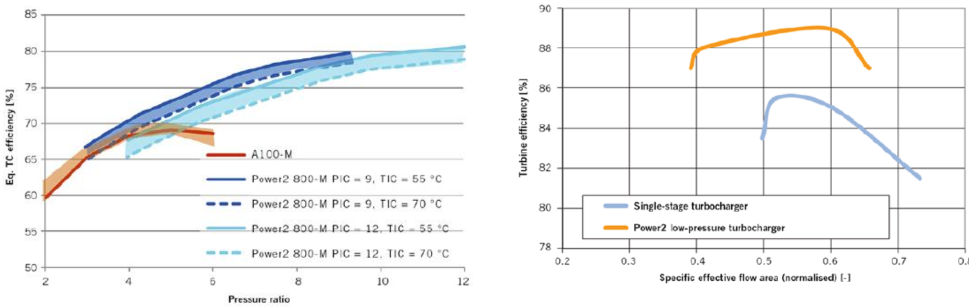

Figure 15. Turbocharging efficiency (left) and low-pressure turbine efficiency of the ABB two-stage T/C [47]

However, designing a two-stage turbocharged engine solution requires solving a number of problems in connection with the mounting of the T/C onto the engine, dealing with the noise and the changed vibration patterns and levels, securing serviceability of the entire system, etc. For example, going from a single-stage to a two-stage T/C increases the mass to be held by the engine by 1.5 to 1.7 times, making a new structural analysis of the entire assembly necessary [48]. Fundamental research is sometimes necessary in order to achieve the engine performance goals under the new conditions; and the literature abounds with papers on the subject of combustion, heat transfer, and gas flow optimization through the valves, e.g. [40].

Thermodynamically efficiency of the large four-stroke engines appears to have been rising at a rate of 0.25% per year (Figure 16, left) for the Diesel and 0.3% for the gas fuel (Figure 16, right) in the last two decades (note that the ordinate in the LHS plot was in the original paper incorrectly labelled, and has been corrected by the present author in the image below). Both trends appear to have continued to the present with the already mentioned Wärtsilä 31 engine (the efficiency figure has not been published, but with the BSFC of 165 g/kWh it is likely to be about 50%), and the newest Jenbacher J920 gas engine genset with an electrical efficiency in excess of 50% has the engine efficiency of more than 51% [52].

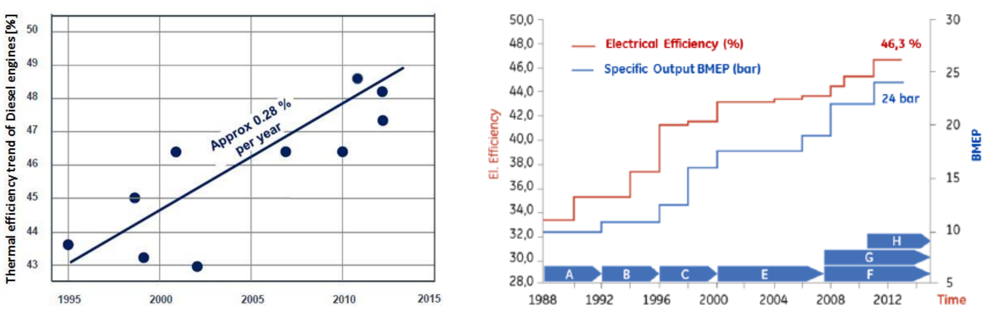

Figure 16. Diesel (left) and gas engine (right) efficiency trends in the past decades, [50], [51] resp

The performance figures of the new J920 gas engine came about through a comprehensive system-based analysis optimization of the already efficient first version of the engine (electrical efficiency of 48.7%, [53]). Referring to the comparison of the respective contributions of the fundamental thermodynamically and mechanical processes in the first and second engine versions, presented in Figure 17 below, it is seen that the performance improvement came about through reductions of the losses due to incomplete combustion, gas exchange, and friction [52].

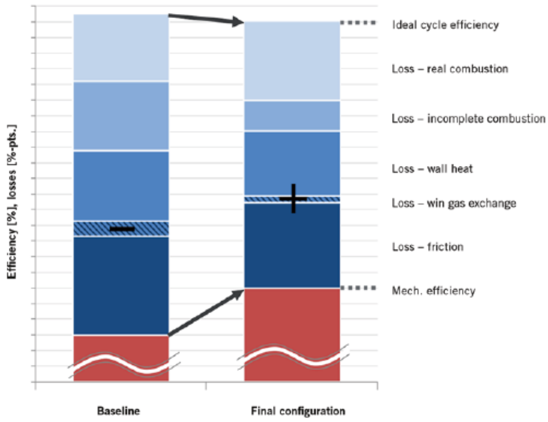

Figure 17. Reduction of losses in the Jenbacher J920 gas engine design process [52]

Summarizing, modern four-stroke large engines are capable of meeting the current exhaust legislation while keeping or improving the engine efficiency, and hold promise for the future. The current development state has been attained by intensive R & D efforts which, given the importance and the omnipresence of these engines, are going to continue.

Nowadays, the four-stroke engine family is characterised by a combination of features, such as:

- Two-stage turbocharging, making the Miller and/or Atkinson cycles possible
- Flexibility with regard to the fuel to use
- Compliance with the IMO Tier III and other equivalent exhaust legislation norms without external exhaust gas treatment when burning gas fuel
- Availability of a combination of intra-engine, e.g. EGR, and external measures for compliance with the norms in the case of liquid fuel oils
- Variable valve timing
- Improvements in the fuel supply to the cylinders (common-rail injection, optimized gas supply)
- Comprehensive electronic control of the entire engine, capable of securing optimal results in the entire operation map; and individual cylinder control has already been reported upon
- Prolonged maintenance intervals of the order of a year's continuous service
- Modular design, facilitating quick repairs but also supporting future upgrades and retrofits.

It is the opinion of the author that the above represents a solid basis for, as formulated in [54], a "future-proof" engine.

4.2 Future R & D directions

It is to be expected that current fine-tuning efforts will be continued and extended, especially as regards the part-load operation. For example, contemporary DF engines must revert to Diesel operation when the load drops below 50% either because of instable operation or the increased emissions. It appears that this problem can be alleviated by selectively switching individual cylinders off [56].

Transient operation is known to give rise to smoke emission (limited by some countries in the ECA), and it has been shown that a better control of the turbocharging can eliminate this problem [55]. Individual cylinder pressure sensors are regularly used in low-speed two-stroke engines, and the trend is expected to carry over to the four-stroke segment. For example, Caterpillar have developed an in-cylinder pressure module (ICPM) that not only measures the maximum pressure, but also evaluates several combustion-relevant parameters, enabling thus the balancing of cylinders in operation [41]. Such efforts then almost inevitably lead to a closed-loop cylinder control, which would be instrumental in further reducing the engine emissions. The Mitsubishi hybrid turbocharger mentioned above within the low-speed two-stroke context has also a fuel saving potential in the four-stroke segment. Tested on a rather small engine (660 kW), it demonstrated a net fuel oil consumption reduction of between 1.9 and 2.8% [58]. It is therefore clear that further R & D efforts are to be expected with this approach, reducing the price being one of the targets. Variable valve timing remains essential for achieving high efficiency and low emissions under varying operating conditions, but it cannot solve the derating problem in low-pressure dual-fuel engines. Essentially, a straightforward solution would be an engine with a variable compression ratio, which has been known in general for a long time. A conference with this topic was held in 2017 [57], showing the current activities at several institutions. One of the concepts is based on an eccentric bushing, integrated in the upper connecting rod eye, which can change the effective connecting rod length in two fixed positions [42]. The VCR idea and theoretical BSFC reduction obtainable with this technology (up to 10 g/kWh with Diesel engines, and up to 8 g/kWh for the gas ones) are shown in Figure 18 below. Intensification of the research is to be expected in this domain.

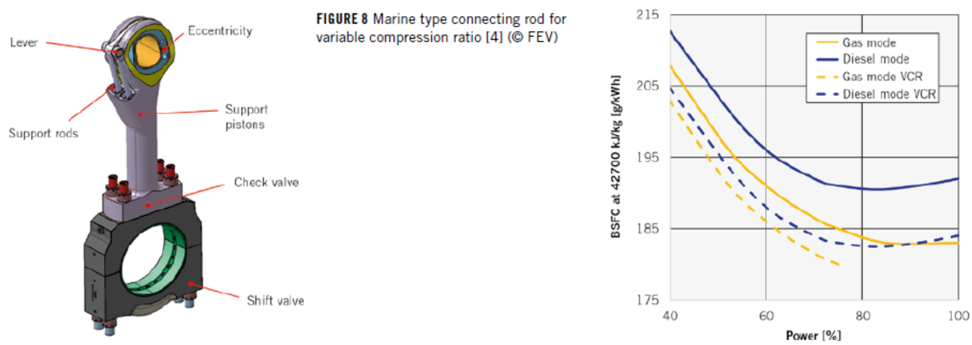

Figure 18. The FEV variable compression ratio proposition and the expected effects [57]

5. CONCLUSIONS

The legislation limiting the emission of hazardous gases has led to unprecedented R & D efforts in the field of large engines, aimed at meeting the emission limits. But it is also their importance for the world economy that has been driving their development, resulting in these engines belonging to the group of the most efficient thermal machines available to the mankind. Due to the work done in the last two decades, all engines offered in the market today comply with the exhaust gas regulations; while in many cases there has also been a considerable progress in improving their efficiency even further.

In the low-speed, two-stroke engine field, compliance with the legislation was brought about mostly by external measures, such as after-treatment of the exhaust gas, and switching to a different fuel in the ECA's. The latter led to the introduction of the dual-fuel engines and their further development into multi-fuel engines. System integration plays a key role in reducing the GHG emissions, in that not only the engine efficiency is of importance, but rather the efficiency of the entire object containing the engine (ship, power plant). For example, this led to the change in the stroke/bore ratio of the ship's main propulsion engine from about 3.5 to up to five in order to enable using large, i.e. more efficient, propellers.

In the case of the four-stroke engines, one technology has played a major role in making possible intra-engine NOx reduction, and this is the turbocharging. Having been known for a long time for making out 10% of the engine price, but bringing about 75% of its power, in its new, two-stage version it provided the high charging pressure required for employing the Miller/Atkinson cycle. Alone or combined with other measures, such as variable valve timing, EGR, SCR, urea or ammonia injection etc. two-stage turbocharging secures full compliance of the current four-stroke engines with the exhaust gas legislation.

Two-stage turbocharging has also led to these engines attaining thermal efficiency of almost 50% with a potential for further increases, especially with gas engines. However, obtaining high efficiency over a broad range of operating conditions, and/or with different fuels, will require further measures and new concepts. One such solution that has been known for a long time, but for cost reasons never utilized in commercial engines, may be the variable compression ratio (VCR). The general trend towards digitalization has been slowly taking grasp of the large engine area. In addition to the local computer control of the engines themselves, which has already become indispensable, optimization of the vehicles (ships, locomotives) and plants (electricity generation) containing large engines, seen as integrated systems is becoming possible. Large amounts of data are already being transferred from ships en route to their control centers, making applications such as e.g. remote monitoring and on-line optimization possible. Summarizing, it can be stated that large Diesel and gas engines will continue to provide the global mass transport with a reliable propulsion power that complies with the environment protection legislation while simultaneously offering ever increasing efficiency and fuel flexibility.

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