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RESEARCH ARTICLE

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Abstract

The article consists of analysis of existing and planned air pollution from ships control and prevention tools such Marpol 73/78 Annex VI, Energy Efficiency Design Index, Energy efficiency operational indicator, Ship energy efficiency management plan, Regulation on the Monitoring Reporting and Verification of shipping emissions, Carbon tax, Maritime emission trading scheme. Norms of these control and prevention tools are difficult to ensue using traditional marine fuels. Pollution rates getting tighter and alternatives have to be used, and some of them have long been known and are not widely used due to objective reasons. Such alternative is natural gas, and its use in ship power plants could reduce concentrations of nitrogen, sulphur, carbon compounds and other pollutants in engine exhaust gas up to acceptable level. The part of maritime sector choosing gas or dual-fuel engines due to tighter pollution rates, and the supply of these engines analyzed in last part of article.

Keywords

Marpol 73/78, non-road engines, natural gas engines, dual-fuel engines, engine market, LNG

1 Introduction

Transport sector is one of the biggest energy consumers in the market resulting in over 26.6% of total energy consumption globally and 33% in Europe and as a result one of the biggest air polluters with a continuing growth projected by the European commission (Eurostat; Industry news). A significant part of this comes from marine transport sector (Colvile et al., 2001). However, transport sectors are governed by different environmental requirements that gradually increase to levels where general fossil fuel such as diesel is no longer sufficient without a significant investment to exhaust gas cleaning. Greatest impact from marine transportation can be seen in SO_x and NO_x pollutant balance (EEB). According to EEB (European Environmental Bureau) data in 2015 SO_x emission in the Baltic Sea was 10000 ton and NO_x emission in the same territory was around 3420 000 ton (BMEPC, 2016). After the implementation of stricter environmental regulations, these emissions are expected to decrease.

The decrease of nitrogen oxides below Tier II requirements is achievable in ships engines by implementing primary emission reduction technologies. This method also allows to come close to tier III requirements but not beyond it and in practice is not yet achievable in commercial ship engines (for example two stage air charge is effective but not yet commercially available) (Lappi et al., 2015). To assure the compliance with Tier III requirements it is necessary implement secondary emission cleaning technologies (Brynnolf et al., 2014). Reduction of SO_x can be achieved in two ways – use of low sulphur fuels or secondary exhaust gas cleaning technologies also known as scrubber. Secondary exhaust gas cleaning technologies are effective way of reducing harmful emissions but they require large investments, essential modernization of propulsion plant and superstructure furthermore installation means docking, loss of revenue and additional costs (Panasiuk, 2012; Panasiuk and Turkina, 2015; Österman, 2013).

In the EU commission scenario (EU Reference Scenario, 2016) it is projected that demand for heavy fuel oil increases at low rates (by 8% by 2020), being progressively substituted by marine diesel oil and liquefied natural gas (LNG). Notably, demand

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for LNG for use as a marine fuel is expected to reach 7.3 Mtoe by 2050 (i.e. 10% of the overall energy needs of international maritime bunkers) (EU Reference Scenario, 2016). The part of natural gas (NG) in global energy market is expected to increase significantly, worldwide NG consumption is projected to increase from 3.4 trillion cubic meters (Tm³) in 2012 to 5.75 Tm³ in 2040 (expected to reach 23.6% – second largest position after coal in 2035) as it is the fastest growing primary energy source (1.6%–1.8% per year) (Cedigaz, 2015; IEO, 2016).

2 Factors restricting maritime transport pollution

The current requirements of Marpol 73/78 Convention annex VI limit the emissions of sulphur and nitrogen oxides. In sulphur emission control zones, the sulphur content of marine fuels from 2015 is limited to 0.1% by mass (kilograms of sulphur per kilogram of fuel) and not in emission control zones up to 3.5% by weight now and up to 0.5% from 2020. Limits of nitrogen oxides emissions are implemented at progressively tightening levels (Tier I, II, III) applicable according to the date of construction / modernization of a ship (Table 1). It is worth noting that Tier 3 limits in NECA (Nitrogen Emission Control Area) zones are up to 75% lower than Tier II (Lindstad and Eskeland, 2016; DNV GL, 2015).

Table 1 Marpol 73/78 Annex VI regulations for NO_x emissions

Tier	Date	NO _x limit, g/kWh		
		n<130 min ⁻¹	130<n<2000 min ⁻¹	n>2000 min ⁻¹
I	2000 01 01	17.0	45·n ^{-0.2}	9.80
II	2011 01 01	14.4	44·n ^{-0.23}	7.70
III*	2016 01 01	3.4	9·n ^{-0.2}	1.96

* Only applicable to ships operating in NECA areas;

* Tier III requirements will take effect in the North American and US Caribbean Emission Control Areas (ECAs) from January 1st 2016 as per the latest MEPC 66 meeting (DNV GL, 2015; Chougale, 2017).

In order to reduce greenhouse gas emissions (CO₂) for new construction vessels, IMO has introduced the Energy Efficiency Design Index (EEDI) for ships between 3,000 and 15,000 DWT. This indicator is intended to encourage ship owners to seek energy efficiency.

The EEDI baseline determines how much CO₂ (g) can a vessel discharge per transport unit, it is based on the global average CO₂ emissions of the ship type and also depends on the size of the vessel. For this indicator, the requirements for ships will be progressively tightened (% indicating how much lower the ship's base value is) and, in the future, their fulfilment may raise engineering challenges or become unachievable by using conventional fuels (Ančić and Šestan, 2015; Bøckmann and Steen, 2016). The Energy Efficiency Operational Indicator (EEOI) was introduced to assess the efficiency of fleet performance. Unlike the EEDI, the EEOI indicator is not mandatory, it is described by the equation (Perera and Brage, 2016):

$$\overline{EEOI} = \frac{\sum_{i=1}^{n_v} \sum_{j=1}^{n_f} F_{Ci,j} C_{Fj}}{\sum_{i=1}^{n_v} M_{cargo,i} D_i} \quad (1)$$

Here: n_v the total number of voyage segments, n_f – the total number of fuel types, F_C – the mass of consumed fuel, C_F – the fuel mass to CO₂ mass conversion factor, M_{cargo} – the cargo carried (tonnes) or work done (number of TEU or passengers) or gross tonnes for passenger ships and D – the distance travelled by the vessel.

Ship Energy Efficiency Management Plan (SEEMP) is a mandatory indicator of ship energy efficiency. It builds on the vessel's EEOI index over a period of time and encourages ship owners to monitor ship energy efficiency indicators as well as implement measures to improve them (Perera and Brage, 2016). Summarizing these measures has one common goal - to reduce CO₂ emissions from ships and other pollutants, but does not specify concrete methods how to achieve it, and this is also not reflected in the EEDI accounting reports (Rehmatulla et al., 2017).

In order to evaluate the effectiveness of implemented technologies EU developed the MRV (Regulation on the Monitoring Reporting and Verification of shipping emissions) regulation, according to this regulation after 2018 ships above 5000 GT that come to the EU or EFTA (European Free Trade Association) ports, will have to prepare CO₂ emission reports. The reports will have to include CO₂ emissions per trip. Reports will have to be validated by independent classification societies and submitted to the European Maritime Safety Organization (EMSA), which will publicize the synthesized material in 2019 (DNV GL). In addition to these control measures, there is also the objective of implementing market measures such as the Maritime emission trading scheme or Carbon tax, but their introduction has become very problematic due to the expected high economic impact of shipping companies and the choice of an efficient accounting system and currently is not reached (Lee et al., 2013; Sheng et al., 2017).

Table 2 Regulatory documents regulating air pollution from ships

Requirement	Limit / Accounting Parameter	Evaluation Criterion	Responsible authority
Marpol 73/78 Annex VI	NO _x emission	g/kWh	IMO
	SO _x emission	Percentage of s in fuel (%)	
EEDI	CO ₂ emission	CO ₂ /transport work unit	-
EEOI			
EU MRV			
SEEMP	Energy efficiency	-	-

The increasing amount of ecological and energy efficiency requirements for marine engines and the rigor of standards make shipbuilders and engine manufacturers look for cost-effective ways to meet standards. One of the most effective

methods is to use NG fuelled engine (Burel et al., 2013; Attah and Bucknall, 2015; Yoo, 2017; Wik and Niemi, 2016). This is especially true for shipping, where the Marpol Convention's requirements for sulphur and nitrogen oxide emissions can be met by using modern NG fuelled engines.

3 Natural gas as a fuel

Usually gaseous fuels are divided into oil, industrial and natural gas. NG is extracted from gas deposits. NG contains methane most of all, and a small amount of other components and impurities. Oil gas is produced in the extraction of oil, it mainly consists of methane, ethane and propane. Industrial gas is formed during oil refining, mainly consists of propane and butane (Jučas, 1992). Gaseous fuels are multicomponent gas mixture, it is useful to present the physical properties of its main components (Table 3) (Karim, 2015; Barmin and Kunis, 2009).

Table 3 Properties of main hydrocarbon fuel gases

Methane	Ethane	Propane	Propene	Butane	Iso-Butane	Butene
Energy content (MJ/kg)						
50.01	47.48	46.35	45.78	45.74	45.59	45.32
Gas density (kg/m ³)						
0.717	1.357	2.019	1.915	2.703	2.668	2.503
Liquid density (kg/l)						
0.466	0.572	0.501	0.519	0.601	0.549	0.607
Liquid energy density (MJ/l)						
23.30	27.16	23.22	23.76	27.49	25.03	27.51
Gas energy density (MJ/m ³)						
32.6	58.4	84.4	79.4	111.4	110.4	113.0
Gas specific gravity (25 °C)						
0.55	1.05	1.55	1.47	2.07	2.06	1.93
Boiling point (°C)						
-164	-89	-42	-47	-0.5	-12	-6.3
Heat of evaporation (kJ/kg)						
509	490	427	438	386	381	359

According to the state, the gas is divided into liquefied petroleum gas (LPG), compressed NG and LNG. Natural gas fuel is well-known as fuel for vessel power plants. The experience of using LNG began in 1964, when the LNG carrier started using the boil off gas as fuel (Einang and Haavik, 2000). By "LNG world shipping" in March of 2017 in service was 103 LNG powered vessels that are not LNG carriers (Corkhill, 2017). Compressed natural gas (CNG) using on ships is not so popular, there are only a few vessels operating on CNG (Stues-Lauridsen et al., 2010) and mainly considered as fuel for inland waters (Dorokhov et al., 2012).

Rapid progress has been made worldwide in recent years in the discovery of new NG deposits. Its increased availability, the need to meet increasingly lower engine exhaust emission

controls, and its relatively low cost have tended to increase its usage as a fuel in a wide variety of applications. The gas has been increasingly viewed as a premium fuel that is in much demand, and may well be for quite some time in the future a prime source of usable fuel energy. The composition of raw NG varies significantly, depending on its source and whether it has been processed for pipeline distribution and consumption or not. Typically, NG as delivered to consumers is suitably processed and composed of about 90% methane, and the remainder is of various concentrations of ethane, propane, butane, and non-fuel-diluent gases, such as nitrogen and carbon dioxide (Jučas, 1992; Karim, 2015).

CNG is produced by compressing the conventional NG to less than 1% of the volume it occupies at standard ambient pressure. CNG technology requires the use of a high-pressure tank and a different refilling system. Ships using CNG require a high-pressure fuel tanks and high-pressure fuel supply system. NG has to be compressed to ~20 MPa, which increases its density to ~140 g/l, it typically correspond on an energy basis to an equivalent amount of gasoline of merely around 30% by volume. The weight, bulk, and cost of the fuel tanks remain a serious limitation to the wide application of CNG, particularly for transport. They can constitute a high cost of the conversion to fuel gas operation (Jučas, 1992; Karim, 2015; Khan et al., 2015).

For efficient transportation, NG is liquefied in special liquidation plants that are usually near the gas source. Liquefied gas is then transported and distributed large distances via specialized LNG tankers (Karim, 2015). The liquidation process effects the composition of NG. Ethane, propane, butanes and heavier hydrocarbons, carbon dioxide and hydrogen sulfides are removed and the gas dried. After the process, remaining NG can have up to 3-4% ethane, 2-3% propane, 2% butane and 1.5% of nitrogen. The density of LNG compared to NG is 600 times greater; this reduces the size of storage and transportation tanks. LNG is colorless, odorless liquid with half the density of water. LNG floats on the surface of water without mixing (Fiodorova, 2011). The use of LNG in transport engines is attractive because of higher energy density in comparison to CNG. Using LNG instead of CNG means lighter fuel system, faster refueling, uniform fuel quality and lower refueling facility costs. Due to liquid state of LNG it can be pressurized to high levels with cryogenic pumps (Karim, 2015). Use of NG in internal combustion engines produces a lot less CO₂, NO_x, SO_x and PM at the same amount of energy, because of lower carbon content in comparison to other fuels [38]. Exhaust gases also contain no solid particles and sulphur oxides. Gas fuels combust more efficiently, than oil fuels or coal, but the emissions depends on not only the fuel type but also on how it is combusted (Fiodorova, 2011). According to different studies, the emissions from ships with dual fuel engines showed significantly lower NO_x and CO₂ emissions in comparison to the gas oil. NO_x emissions can be reduced up to

90% and CO₂ up to 20% but hydrocarbon and carbon monoxide emissions were higher Anderson et al., 2015; Thomson et al., 2015; IMO, 2016; GB Transport Committee, 2012).

NG contains virtually no sulphur and therefore the engine can operate without restriction in SECA areas, but after the entry into force of Marpol Annex VI third level requirements for nitrogen oxide emissions, in NECA zones, the use of gas alone is not always sufficient (GB Transport Committee, 2012; Lloyd's register):

- gas engines operating in the Otto or Miler cycle can achieve compliance with Marpol Tier III requirements;
- dual-fuel engines are certified at the Tier II level (when using liquid fuel) and Marpol Tier III (in case of fuel gas injection) using a special test procedure. The dual-fuel engine can also be certified as a gas engine, but then liquid fuel can only be used in emergencies.

4 Supply of non-road piston IC engines able operate on natural gas

Natural gas use in marine engine in many cases ensures that vessel allowed to operate in the emission control zones (ECA) without any additional exhaust gas aftertreatment systems. Marine engine producers “MAN Diesel & Turbo SE”, “Wärtsilä”, “Caterpillar Inc.”, “Hyundai Heavy Industries”, “Kawasaki Heavy Industries”, “Rolls–Royce” (Wärtsilä, 2015; MAN Diesel & Turbo; Wartsila Engines & Generating; CAT; Hyundai; Kawasaki; Rolls–Royce) state that their marine gas engines ensure Marpol 73/78 Tier III requirements. Other advantage of NG use is related to dual-fuel (diesel/heavy fuel oil-NG) engines operation when ship owners able to optimise their costs due to price difference between liquid and gaseous fuels.

The principle of NG use in marine engines is close to liquid fuel one. One of the ways is more primitive – when NG realized in Otto cycle (spark ignition engines) and NG is the only one fuel. Such engines generate power in the range of ~25–11000 kW. This type engines are rarely classified as marine engines because in many cases they could be customized (usually they are purposed) for other sectors (stationary energy, mining, special purpose transport, oil industry, etc.). “Kawasaki Heavy Industries” (Kawasaki), “Rolls–Royce” (Rolls–Royce) and “General Electric” (General electric) spark ignition engines are presented as marine engines due to their mass an power, however, if necessary, they can work in stationary power units. Market of various purpose gas engines is rich in participants: “MAN Diesel & Turbo SE”, “Dresser-rand”, “MWM”, “MTU”, “Weichai”, “Perkins”, “Cummins”, “Deutz”, “Caterpillar Inc.”, etc.

4.1 Spark ignition gas engines

In spark ignition (SI) piston engines NG, as a fuel, used via usual Otto cycle when the in-cylinder charge ignites from an additional source (spark plug). Usually NG is injected into intake air flow (intake manifold) and ignited in cylinder

by spark plug. Comparing to dual-fuel technology, the use of NG in SI engines is more primitive, however a part of engine producers improve the design – use pre-chambers with spark plug (“MAN Diesel & Turbo SE”, “Wärtsilä” and etc.), others investing in ignition control, improving the Miller cycle (MTU, etc.), and etc. The main part of SI engines are purposed and used in land – electricity production, special purpose transport, oil extraction engineering units, etc. These engines are not widespread in shipping sector due to objective reasons – to avoid restrictions related to wide operation areas (lack of port infrastructure for NG bunkering), and for that reason main part of ships are designed to use liquid fuels: Marine Gas Oil (MGO), Marine Diesel Oil (MDO), Heavy Fuel Oil (HFO). The latter are available in practically all over the world, and the gaseous fuel supply infrastructure is less developed than liquid fuel. However the gas engine use in ship power plants becomes more relevant due to stricter pollution control requirements in Emission Control Areas (ECAs) and in the same time bunkering problems are solving and new projects are being implemented.

The analysis of marine SI engines is difficult due to the mentioned reason – in many cases, engines are multipurpose and manufacturers do not detail their purpose or field of application. However high power “Bergen” (“Rolls–Royce”) engines (Rolls–Royce), that purposed for ship propulsion and work with electric generator, must be mentioned: C26:33L (engine modifications C26:33L6PG, C26:33L8PG, C26:33L9PG 1460–2430 kW, at 900/1000 min⁻¹), B35:40L9PG (3940 kW, at 750 min⁻¹), B35:40V12PG (5700 kW, at 750 min⁻¹). As well “Kawasaki Heavy Industries” supplies four stroke marine engine series L30KG (6, 8 and 9 cylinders, 2670–4005 kW, at 750 min⁻¹) that can be used as propulsion engines or in gen-set units (Kawasaki). “General Electric” piston gas engine series “JENBACHER TYPE 2/3/4/6” (General electric) which includes engines:

- J208 (299 and 335 ekW, 50/60 Hz);
- J312 (405 and 633 ekW, 50/60 Hz), J316 (835 and 848 ekW, 50/60 Hz), J320 (1067 and 1059 ekW, 50/60 Hz);
- J412 (850 ekW, 50/60 Hz), J416 (1137 ekW, 50/60 Hz), J420 (1426 ekW, 50/60 Hz);
- J612 (2004 and 1979 ekW, 50/60 Hz), J616 (2679 and 2649 ekW, 50/60 Hz), J620 (3360 and 3325 ekW, 50/60 Hz), J624 (4401 ekW, 50/60 Hz);
- J920 Flextra (10400 and 9350 ekW, 50/60 Hz).

As well company “General Electric” supplies engine series “WAUKESHA” for transport means and stationary energy units (General electric):

- VGF48GSID, VGF48GL/GLD, VGF48GL (LCR) – 50 Hz: 625/685/625 ekW, 60 Hz: 750/830/750 ekW;
- VGF36GSID, VGF36GL/GLD, VGF36GL (LCR) – 50 Hz: 475/515/475 ekW, 60 Hz: 560/620/560 ekW;
- VGF24GSID, VGF24GL/GLD, VGF24GL (LCR) – 50/60 Hz: 375/415/375 ekW;

- VGF18GSID, VGF18GL/GLD, VGF18L (LCR) – 50 Hz: 230/255/234 ekW, 60 Hz: 230/307/279 ekW;
- VHP9504GSI emPact, VHP7104GSI emPact, VHP7100GSI S4 emPact, VHP7100GL 50 Hz: 1460/1100/875/875 ekW, 60 Hz: 1600/1200/1050/1050 ekW;
- MobiFlex VHP7104GSI, VHP L7044GSI, VHP5904GSI, VHPL5794GSI (50 Hz: 1153/1153/947/947 kW, 60 Hz: 1253/1253/1029/1029 kW);
- 16V275GL+, 12V275GL+ (50 Hz: 3605/2705 ekW, 60 Hz: 3215/2415 kW).

Multipurpose low power (37–580 kW) four stroke SI gas engines (E0834, E0836, E2676, E2876, E2848, E3268, E2842, E3262) are supplied into market by company “MAN Diesel & Turbo SE” (MAN Diesel & Turbo). As well this company supplies high power SI gas gen-sets that have power: with 51/60G and 51/60G TS (two-stage turbocharged) series engines 18654–20431 ekW (500 and 514 min⁻¹), 35/44G and 35/44G TS (two-stage turbocharged) 10420–10027 ekW and 6945–12214 ekW (at 720 and 750 min⁻¹) respectively.

Company “Wärtsilä” offers the most powerful 4 stroke SI gas engine 18V50SG (18810 kW/18321 ekW at 50 Hz/500 min⁻¹ and 19260 kW/18759 ekW at 60 Hz/514 min⁻¹) and slightly less powerful gas gen-sets 9/16/20 L34SG and 20 L34SG with turbo generator, whose power varies in range of 4380–9520 ekW (50/60 Hz at 750/720 min⁻¹ respectively) (Wartsila Engines).

Company “Caterpillar Inc.” has one of the largest supply capacities of SI gas engines. The large part of these engines are purposed to work in gen-set units, other part purposed for vehicle propulsion systems. “Caterpillar Inc.” engines able to use NG, biogas, propane, coal gas, well gas (detailed information presented in manufacturer documentation). Also the supply of “Caterpillar Inc.” engines gives possibility to be flexible choosing engine according ranges of size, power, revolutions and etc. The company produces multipurpose (for industry, small energy, cogeneration, landfill gas recovery, mining, oil and gas extraction industry, special purpose vehicles, etc.) SI four stroke engines that able to work on different kind of gas (CAT), however these engines are rarely used in ships due to specifics of gaseous fuels use in waterborne transport:

- for electricity generation:
 - low power engines (DG30-2, DG50-2, DG60-2, DG80-2, DG100-2, DG125-2, G3306, DG150-2, G3406), electric power range is 30–235 ekW (at 1500/1800 min⁻¹);
 - average power (400–1041 ekW at 1200/1500/1800 min⁻¹) engines (CG132-8, G3412, G3508A, CG132-12, G3512A, CG132-16, G3512E, G3516A);
 - high power engines (CG170-12, G3516B, CG170-16, G3516E, G3516C, CG170-20, G3516H, G3520E, G3520C, CG260-12, CG260-16) in gen-set

units generate electric power 1200–4500 ekW (at 900/1000/1200/1500/1800 min⁻¹);

- for direct power transmission:
 - low power engines (G3304, G3306, G3406, G3408) that power varies in range of 71–317 kW at 1500 or 1800 min⁻¹;
 - average power engines (G3412, G3508/G3508B, G3512/G3512B, G3516/G3516B), their power range is 475–1030 kW at 1200/1400/1800 min⁻¹;
 - high power engines (G3520/G3520B) that maximal power reach 1285 kW;
- gas compression engines for oil and gas industry:
 - low power engines (G3304B, G3306B, G3406, G3408, G3408C, CG137-8) that power varies in range of 71–317 kW at 1200/1400/1800 min⁻¹;
 - average power engines (G3412, CG137-12, G3508, G308B, G3512, G3512B, G3516, G3516B, G3516J) their power range is 447–1030 kW at 1400/1800 min⁻¹;
 - high power engines (G3520B, G3606, G3608, G3612, G3616, G3606 A4, G3608 A4, G3612 A4, G3616 A4, G12CM34, G16CM34) that power range is 1100–6100 kW at 450/1000 min⁻¹

SI gas engines “CAT” have wide application possibilities and due to this a part of mentioned engine models are repeated in different purpose engine groups. Engine power groups (low/average/high power) were chosen after “Caterpillar Inc.” SI gas engine supply analysis: low power – up to 400 kW (±10%); average – 400–1000 kW (±10 %); high power – from 1000 kW (±10 %).

SI gas engines are not popular in merchant shipping for obvious reasons – less operation time till maintenance, lower relative power (kW/cylinder), lower torque, specificity of gaseous fuel bunkering, fuel selection inflexibility and etc.

4.2 Marine dual-fuel engines

The supply market of dual-fuel (diesel-NG) marine engines is dominated by the several large companies that have many years of experience in diesel engines production field. This market is dominated by companies such as “MAN Diesel & Turbo SE”, “Wärtsilä”, “Caterpillar Inc.” and “Hyundai Heavy Industries”. Also a part of mentioned companies supplies SI gas engines. Other companies (“Cummins”, “Yanmar” and “Weichai”) have a small supply in the low power engine segment, which are purposed to ensure energy or power needs in mining, oil industry, etc.

Company’s “MAN Diesel & Turbo SE” attention, apart from usual IC engine manufacture, focused on dual-fuel engine manufacture. This company supplies various power and speed engines into market, they ensure Marpol 73/78 Annex VI Tier III (further Tier III) when operate in dual-fuel mode: four stroke propulsion and auxiliary engines L35/44DF (3060–5300 kW),

L51/60DF (6–9 cylinders, 5850–9000 kW), V51/60DF (12, 14, 16, 18 cylinders, 11700–23800 kW) and L28/32SDF (5–9 cylinders, 1000–1800 kW) with low pressure gas injection in to intake manifold technology. Also market is supplied by two stroke high power series ME modified engines which can partially replace oil products consumption: low speed engine series ME–GI with high pressure direct gas injection S70-ME-C8-GI (16350–26160 kW), S65-ME-C8-GI (14350–22960 kW) and S60-ME-C8-GI (11900–19040 kW); ME-LGI series with volatile liquids or liquid gas (methanol, ethanol, dimethyl ether and liquefied petroleum gas) direct injection in cylinder; ME-LGIM engines which use a main part of methanol and pilot portion is oil fuel (HFO, MDO or MGO). The distribution of power ranges is presented in Fig. 1.

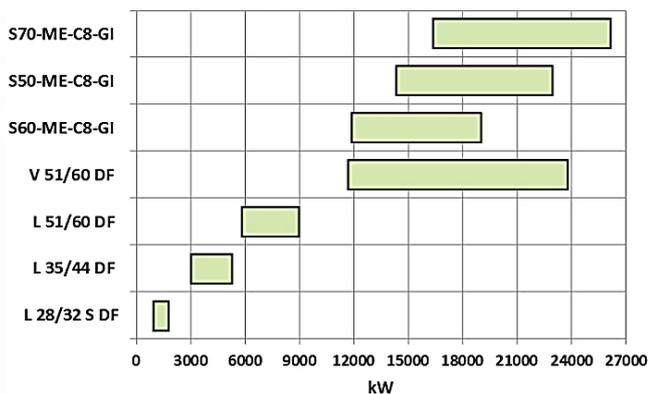


Fig. 1 The distribution of “MAN Diesel & Turbo SE” dual-fuel engines power range

The supply of “CAT” SI gas engines is much bigger than supply of dual-fuel engines purposed for merchant shipping and stationary energy units. “CAT” engines that able to use gas in dual-fuel cycle (MDO/HFO-NG) could be divided into two groups – propulsion engines and gen-set purpose (Fig. 2):

- propulsion engines manufactured under “MaK” brand and three different power engine models are supplied into market: M 34 DF (6, 8 or 9 cylinders, 3060–4770 kW, at 720/750 min⁻¹), M 46 DF (6–9 cylinders, 5400–8685 kW, at 500/514 min⁻¹) and VM 46 DF (12 and 16 “V” form, 10800–15440 kW, at 500/514 min⁻¹). Same engines are used as gen-set IC engines, such gen-sets generates electric power in a range of 2934–14807 ekW;
- powerful IC engines (6CM34DF, 8CM34DF, 6CM46DF, 7CM46DF, 8CM46DF, 12CM46DF, 16CM46DF) together with electric generators generate 2880–14976 ekW at 720 min⁻¹ (60 Hz) and 750 min⁻¹ (50 Hz).

“Wärtsilä” company is another strong and well-known manufacturer of marine gas engines (Wartsila Engines). This company, apart usual diesel engine production, manufactures dual-fuel engines with high pressure gas injection into cylinder technology. These engines (Fig. 3) ensure Marpol Tier III requirements in dual-fuel mode:

- four stroke engine for gen-set units, series 20DF (6, 8, 9 cylinders 1110–1665 kW at 1200 min⁻¹) with low pressure gas injection system. These engines are able to run on HFO-gas, distillates-gas and HFO-distillates fuel modes generating 185 kW of power per cylinder. Also the manufacturer claims that this series engines able to run on biofuels;
- four stroke engine series 31DF (“V” form 8, 10, 12, 14 and 16 cylinders, 4200–8800 kW at 720 and 750 min⁻¹) for propulsion (could be used in gen-set units) that is made on “Wärtsilä” 31 engine series base. This series have 3 modifications that able to run on different fuel modes: diesel fuel, dual-fuel and pure gas. 31 diesel engine series is included in the Guinness Book of World Records as the most effective 4 stroke diesel engine series;
- four stroke engine series 34DF for propulsion, however it can be used as gen-set IC engine. This series engines have 6, 8 or 9 in-line cylinders that generates power in the range of 3000–4500 kW. 12 and 16 cylinders “V” form engines generate 6000 and 8000 kW at 750 min⁻¹;
- four stroke engine series 46DF for propulsion (could be used in gen-set units) which has a very good power-mass ratio. The power per cylinder reaches 1045 kW or 1145 kW at 600 min⁻¹. Engine series equipped by low pressure gas injection technology;
- high power four stroke engine series 50DF that consists of 6, 8 and 9 in-line cylinders engines (6/8/9L50DF, 5700–8550 kW) and “V” form 12, 16 and 18 cylinders engines (12/16/18V50DF, 11400–17550 kW). Engines are flexible for different fuel use – with low pressure gas injection system could operate in chosen fuel modes: HFO-gas, distillates-gas and HFO-distillates. They generate 950 or 975 kW/cylinder at (500/514 min⁻¹) and usually these engines are used in gen-set units.

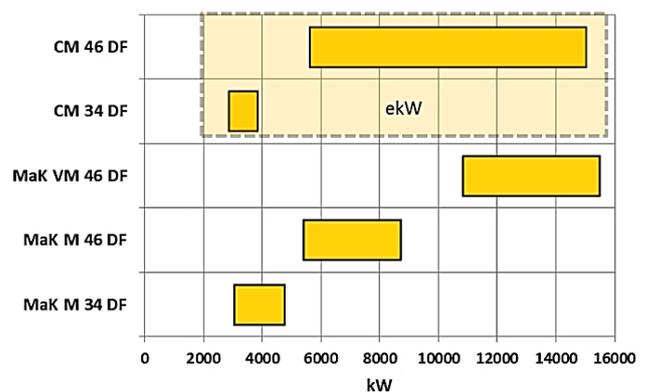


Fig. 2 The distribution of “Caterpillar Inc.” and “MaK” dual-fuel engines power range

The company “Wärtsilä” is in close cooperation with the Swiss company “Winterthur gas and diesel” (“WinGD”), together they supply high power two stroke low speed dual-fuel

engines (RT-flex50DF, W-X52DF, W-X62DF, W-X72DF, W-X82DF, W-X92DF) for propulsion (Wingd). The rated speed on these engines varies in range of 65–124 min⁻¹, power – 7450–63840 kW (Fig. 4), bore – 500–920 mm and stroke 2050–3468 mm.

“HiMSEN” is dual-fuel engine series from company “Hyundai Heavy Industries” (Hyundai). The series consists of 6–9 in-line cylinders engines H35DF (2880–4320 kW at 720/750 min⁻¹) and 12, 14, 16, 18 and 20 “V” form cylinders engines H35DFV (5760–9600 kW at 720/750 min⁻¹). Engines HiMSEN H35DF and H35DFV used in gen-set units, and ensure Marpol Tier II requirements when running on diesel fuel and Marpol Tier III in dual-fuel mode.

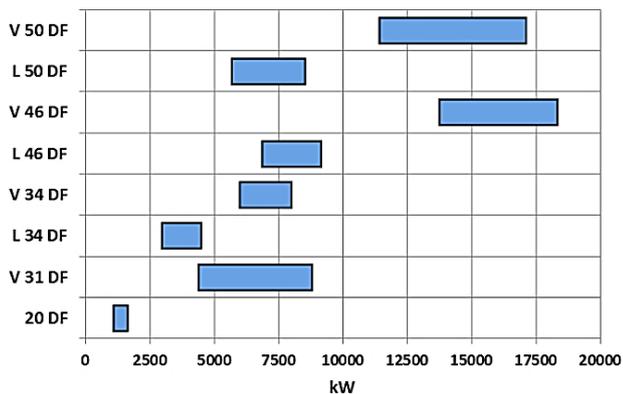


Fig. 3 The distribution of “Wärtsilä” dual-fuel engines power range

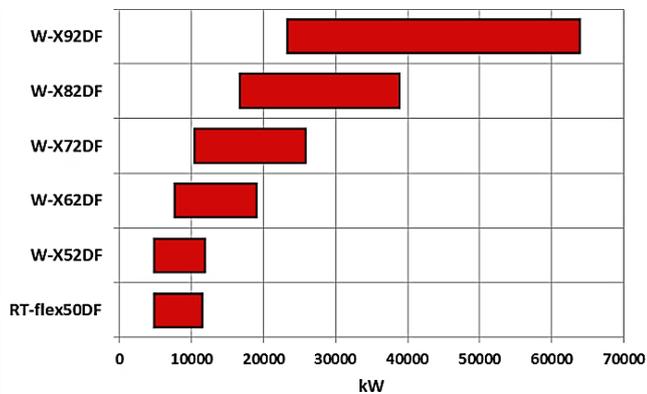


Fig. 4 The distribution of “Winterthur gas and diesel” dual-fuel engines power range

Also the single cases of well-known companies manufactured dual-fuel engines supply could be found in market. Company “Cummins” supplies the 4 stroke dual-fuel engine series Dual Fuel QSK50 (1044–1193 kW) with low pressure gas injection system, they purposed to ensure the energy needs of oil wells on land (Cummins), also can be used as a propulsion engine on small ships and in gen-set unit. Company “Yanmar” supplies marine engine 6EY26DF (Yanmar), which rated power is 1533 kW (at 750 min⁻¹). Chinese company “Weichai Heavy Machinery” represents (Weichai) their dual-fuel products – 6170 (410 kW) and 12M26 (500 and 700 kW at 1900 min⁻¹).

Analysis shows that the main part of supplied dual-fuel engines is engines above ~1000 kW and the supply of such power engines is week. So this case shows that mainly all market focused on ocean (sea) going ships, and small tonnage inland ships almost have no supply of dual-fuel engines up to ~1000 kW.

5 Conclusion

As pollution prevention becomes more and more important, pollution control tools are getting stricter. The allowed limits for SO_x and NO_x emission becomes lower in ECAs which are regulated by IMO Marpol Annex VI. Also the tools came into force or are planned to be involved into pollution control: Energy Efficiency Operational Indicator (EEOI), Ship Energy Efficiency Management Plan (SEEMP), Regulation on the Monitoring Reporting and Verification of shipping emissions (MRV), Maritime emission trading scheme (planned) and Carbon tax (planned).

The process of NG utilization in power plant is well-known for a long time and used wide in stationary energy sector as an alternative for liquid fuels. However NG powered ships are not common in shipping due to obvious reasons: competitive liquid fuel price, bunkering infrastructure specifics, the ensure cryogenic conditions during transport as a cargo and as a fuel (in the case of LNG) and etc.

Natural gas use in ship power plants makes lower rates of sulphur, nitrogen, carbon and other compounds concentration in exhaust gas. Strengthening environmental requirements lead the higher level of NG use especially in pollution in sensitive regions (Emission Controlled Areas).

In general view, the largest non-road purpose engine manufacturers “MAN Diesel & Turbo SE”, “Wärtsilä”, “Caterpillar Inc.”, “Hyundai Heavy Industries”, “Kawasaki Heavy Industries”, “Rolls-Royce” and etc., are ready to ensure the demand of gas using engine market. Comparing to spark ignition engines, dual-fuel engines are more preferable in shipping sector due to fuel use flexibility – to maneuver between the market fuel prices and the ensure of environmental requirements. However the supply of spark ignition gas engines is much bigger than dual-fuel due, this fact determined by the stationary energy sector with its demand of gas utilization units.

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