ALTERNATIVE PROPULSION PLANTS FOR MODERN LNG CARRIERS

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Abstract. This paper shows the latest evolution trends of propulsion plants of modern LNG tankers. Features of conventional and advanced steam plants were confronted with propulsion plants such as Dual Fuel – Diesel electric and plants equipped with slow speed two stroke diesel engines. Propulsion plants were compared in terms of plant efficiency, reliability and environmental. The shipyard's order book and the active fleet of LNG carriers with a capacity above 65000 m^3 were analyzed.

Keywords: tanker, propulsion plant, dual fuel diesel engine, steam propulsion plant, thermal efficiency

INTRODUCTION

Marine transport of natural gas over the last decade has become increasingly common. This is due to the technical difficulties of gas transmission over long distances. The number of new built vessels and *LNG* (Liquefied Natural Gas) terminals constructed around the world confirms that. Just in 2016 maritime transport of natural gas has recorded a 5% increase compared to 2015.

Number of ordered and operated vessels constantly increase. In January 2017 world fleet of *LNG* carriers was consisted of 439 vessels (capacity above 65000 m^3), with total capacity of 64 million m^3 of liquefied gas. In years 2000-2015 the number of *LNG* carriers has increased 4 times. Only in years 2011-2013 there was a significant downturn in that trend caused by economic crisis. However, in 2015 and 2016 there were 29 and 31 new vessels were commissioned. Analysis of shipyards order book shows that 120 new *LNG* carriers should be built by 2020.

Increase in demand for natural gas results from its attractive price as well as its high calorific value. Furthermore it is much more environmentally friendly than other fossil fuels. Use of *LNG* as a fuel results in reduction of NO_x by 90%, CO_2 by 20% and eliminates emission of SO_x and particulate matter compared to *HFO* (Heavy Fuel Oil). By 2016, natural gas has covered up to a quarter of the world's energy demand, of which 10% was transported in liquefied form, mostly by sea.

OVERVIEW OF PROPULSION PLANTS FOR MODERN LNG CARRIERS

Up to the first decade of XXI century steam propulsion plant was the leading solution because of the possibility to utilise *BOG* (Boil Off Gas) as a fuel for boilers. This trend has changed at the turn of years 2005-2010 (IGU World LNG Report (2017)). Increasing price of *LNG* in years 2001-2009 (Fig. 1) forced shipping industry to research new technologies and solution for gas carrier propulsion plants.

The most common became diesel electric plant (*DFDE* – Dual Fuel Diesel Electric), for the drive of witch dual fuel, medium speed, diesel engine are used. On further development levels triple fuel engines were applied (*TFDE*). Widely common were solution with slow speed diesel engines fuelled by residual fuel (*HFO*). For that last solution it is necessary to fit Reliquefaction plant. It is so called *DRL* propulsion plant (Diesel with Reliquefaction Plant).

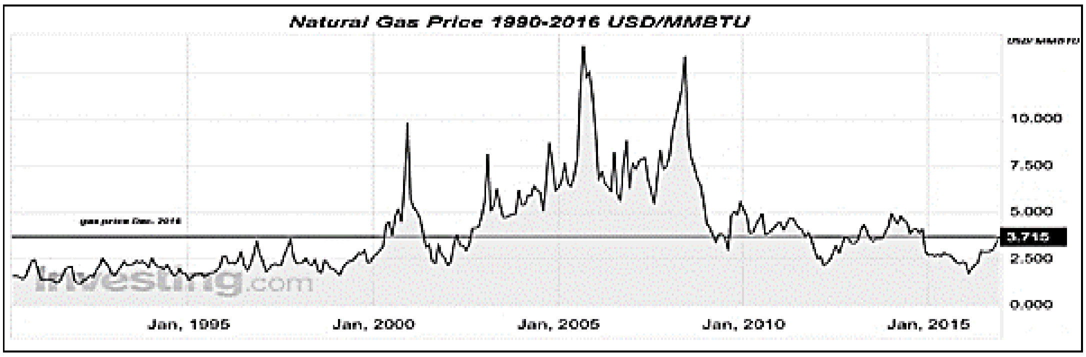
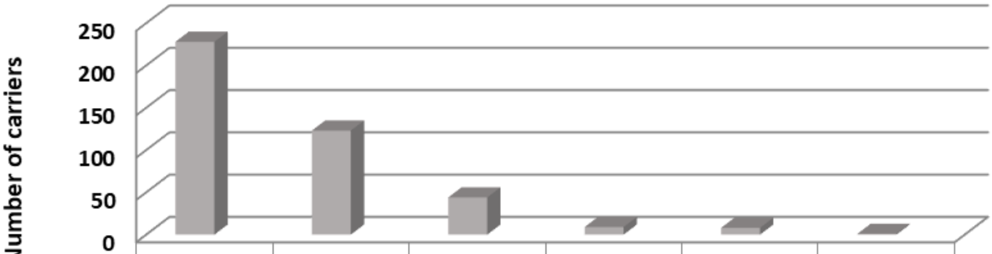


Fig. 1. Natural gas price 1990-2016 in relations to 1MMBTU.
Source: www.investing.com 2016

In years 2004-2016, 123 new vessels were equipped with *DFDE/TFDE* plant, which accounted for 30% of whole fleet (Fig. 2). At the same time 146 steam turbine propelled vessels were commissioned, but only 19 ships on years 2010-2015, part of which were equipped with modified high energy efficient steam plants. 45 vessels with slow speed diesel engines fuelled by fuel oil only were launched between 2005-2010. Naturally boiled off gas in this plant had to be re-liquefied. From an economic point of view, this solution was justified by assuming a high gas price. The decrease of gas price (Fig. 1), has resulted in resignation of new builds of this type and development works on the modification of existing plant to adapt to be fuelled by *BOG*. The first vessel was modified in the second quarter of 2015 (m/v Rasheeda). As the technology advances, new vessels with dual fuel slow speed engines were introduced. Example of that engine is *ME-GI* type engine made by MAN Diesel and Turbo (*MDT*), which power range is 3.5-82 MW depending on model and number of cylinders. First *LNG* carrier equipped with dual fuel slow speed engine was commissioned in 2016.



	STEAM	DFDE / TFDE	SSD/DRL	MEGI	REHEAT STEAM	MEGI/SSD
Quantity	228	123	44	9	8	1
Precentage	55,2	29,8	10,7	2,2	1,9	0,2

Fig. 2. Solutions of existing LNG carrier's propulsion plants (at May 2017).

An analysis of shipyard order books, shown on Fig. 3, shows that DFDE/TFDE propulsion plant is still the preferable solution, due to their claimed higher thermal efficiency over steam plant. In recent years, 50 vessels have been ordered with low speed two stroke diesel engines adapted for BOG utilisation as fuel (MEGI + xDF). This represents 44% of all ordered units. These vessels are equipped with re-liquefaction plant as an alternative method to control the pressure of cargo tanks (BOG treatment). DF SSD plant (Dual Fuel Slow Speed Diesel engine) completely supplanted DRL systems from the market, offering higher thermal efficiency and operational flexibility.

Order book also includes 14 vessels with steam propulsion plant, 7 of which are advanced steam system with higher steam parameters and used steam reheat systems. These carriers are mainly intended for operation in long-term charters.

In 2013 Lloyd's Register approved in principle first *LNG* carrier design used *COGES* (COmbined Gas turbine Electric and Steam turbine) propulsion plant fuelled by *LNG*. However, since then none of the shipyards have received a contract for vessel propelled by *COGES* system.

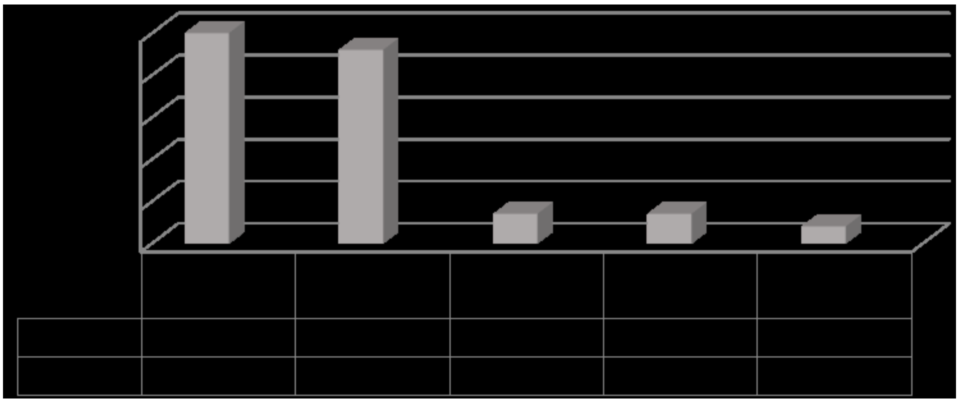


Fig. 3. LNG carrier's propulsion plants on order (at May 2017).

CHARACTERISTIC OF PROPULSION PLANTS FOR MODERN LNG CARRIERS

The following section shows overview of the propulsion systems of existing *LNG* carriers as well as the two shipyard's proposed designs for new vessels.

Conventional and advanced steam plants

Nowadays, propulsion plant using steam turbines have been applied mainly on nuclear navy ships and on *LNG* carriers. Maritime steam plant, which simplified diagram is shown on Fig. 4 works according to Clausiu's-Rankine's cycle.

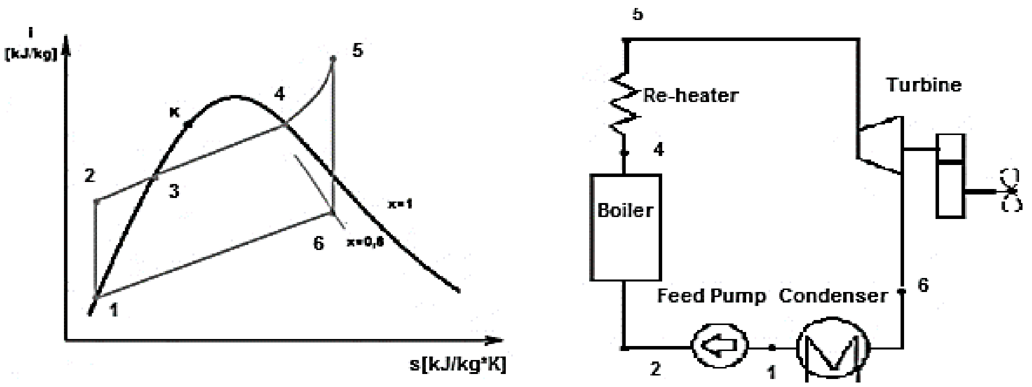


Fig. 4. Clausiu's-Rankine's cycle in the i-s system and simplified diagram of the steam propulsion system for *LNG* carrier.

Source: Kosowski K., 2005

Steam turbine plant consists of steam boiler, main turbine set, condenser, and feed pump. Efficiency of theoretical cycle, assumes perfect transformations, is in range η_{CR} = 0.37-0.44. The effective system efficiency, assuming boiler efficiency η_k= 0,85-0,9 and turbine internal efficiency η_{Tw}= 0.8-0.85 is in range η_{CST} = 0.25-0.34.

Conventional Steam Turbine plant (*CST*), data of whose are presented in Table 1, consist of 2 steam boilers produce superheated steam (pressure p_5 = 60 Bar, t_5 = 515-525°C), compound steam turbine, vacuum condenser and feed water system with turbo feed pumps and regenerative heat exchanger.

Advanced steam plant: *ART* (Advanced Reheat Turbine) and *UST* (Ultra Steam Turbine), data of whose are shown in Table 1, are the development of the conventional plants by increasing condition of superheated steam, applied improved steam cycle with reheat and increased number of regenerative heaters.

As a result of further research of steam plant efficiency improvement, an innovative concept has been presented by Mitsubishi Heavy Industry. *STaGE* (Steam Turbine and Gas Engine) is a further development of *Sayaendo UST*. In this new solution twin screw propulsion is applied, one of which is driven by steam turbine via gearbox and form part of *UST* plant. The other propeller is driven by the electric motor which is fed by *DFDE* plant. Combination of both solutions allows recovery of significant waste energy from diesel engines and utilise it in regenerative heaters in the boiler feed water system of steam part of propulsion plant. According to manufacturer data, application of *STaGE* concept in conjunction with new hull design and additional cover for MOSS cargo domes to decrease air resistance, allow an increase efficiency by approximately 20% compared to the *Sayaendo UST* propulsion plant.

Table 1.
Development of characteristics and working condition of LNG carrier's steam propulsion plants

	CST -1990	CST -2003	ART - KHI	UST - MHI	STaGE- MHI
Class/capacity	CST - 1990 125 000m^3	CST - 2003 138 000m^3	ART -2011 177 000m^3	UST - 2014 145 000m^3	STaGE 2018 177 000m^3
Cycle	CR - REGENERATIVE	CR - REGENERATIVE	CR – REHEAT AND REGENERATIVE	CR – REHEAT AND REGENERATIVE	CR - REHEAT AND REGENERATIVE+ OTTO (DFDE)
Steam Boilers	2x Mitsui MSD 40 ER	2x KHI - UME 65/50	2x KHI - UTR-II	2x MHI - MB	MHI – MB
Superheated steam condition	60 bar/515°C	61 bar/525°C	120 bar/560°C	100 bar/560°C	100 bar/560°C
Reheat steam condition	xxxxxxxx	xxxxxxxxx	No data 560°C	20 bar/560°C	20 ba /560°C
Steam boiler capacity	2x 40 T/h	2x 65 T/h	2x 54 T/h	No data	No data
Turbine model	MHI - MS24-2	KHI - UA 400	KHI - URA 450	MHI- MR36-2	MHI- MR-II + WARTSILA 3x 6L50DF
Turbine Type No. and type of stages	HP 1x Curtis 7 Rateau LP - 4 Rateau 4 Reaction	HP - 1 Curtis, 8 Rateau LP - 4 Rateau 4 Reaction	HP - 10 stages IP – brak danych LP - 10 stages	HP - 1 Curtis 5 Rateau IP - 6 Rateau LP - 4 Rateau 4 reaction	HP - 1 Curtis 5 Rateau IP - 6 Rateau LP - 4 Rateau 4 reaction
Power Output	17140 kW	29500 kW	27000 kW	30000 kW	ok 30000 kW
No. Of bleeds	2 (IP/LP)	3(HP/IP/LP)	3(HP/IP/LP)	3(HP/IP/LP)	3(HP/IP/LP)
Condenser vacuum	722 mmHg	722 mmHg	722 mmHg	722 mmHg	722 mmHg
No. Of regenerative heaters	3	5	7	4/6	No data
Feed water temperature	138°C	145°C	No data	138°C	138°C
Daily FO consumption	130 T/day	200 T/day	160 T/day	178 T/day	No data
Specific fuel consumption	310 g/kWh	285 g/kWh	246 g/kWh	248g/kWh	~230 g/kWh
Specific steam consumption at MCR	4.67 kg/kWh	4.07 kg/kWh	3.70 kg/kWh	3.15 kg/kWh	No data
Aux. steam system	Common – desuperheated steam	LPSG – Low pressure steam generator	LPSG – Low pressure steam generator	Common - desuperheated steam	Common - desuperheated steam
Electric power plant configuration	1x T/G 2x D/G	2x T/G 1x D/G	1x T/G 2x D/G + shaft generator	2x T/G 1x D/G + shaft generator	3x D/G

Source: Adamkiewicz A. & Grzesiak S. 2016

Dual Fuel Diesel Electric propulsion plant

In 2004 the first *LNG* carrier propelled by *DFDE* propulsion system was commissioned. This concept is well known and widely used on passenger ships and car ferries, where the height of a conventional main engine was limited, so medium speed engines were used for main propulsion. However innovative for maritime industry was the usage of dual fuel engines. Generator engines were designed to burn both fuel oil and boil off gas. This solution was an adaptation of the shore based power plants for the maritime industry.

DFDE/TFDE plant, shown on Fig. 5, consists of generation sets and electrical transmissions, driving fixed pitch propeller via reduction gearbox. An alternative solution is the podded propulsion unit (widely known as Azipod). *PEM* (Propulsion Electric Motors) are fed from main switchboard via step-down transformer and thyritor converter in order to synchronize the frequency of current according to requested shaft speed.

Dual fuel, medium speed diesel engine, which are working according to Otto cycle are used to powered *DFDE* propulsion plant. In most solution the gas is supplied to the combustion chamber by means of gas admission valve located on the charge air inlet line to the cylinder, under pressure of approximately 0.5 bar higher than engine scavenge air pressure. Due to poor auto ignition properties of methane, an external source of energy to initiate the combustion process is required. This is done by the injection of small amount of pilot fuel into the combustion chamber. The amount of gas fed to the unit is controlled by opening time of the gas valve.

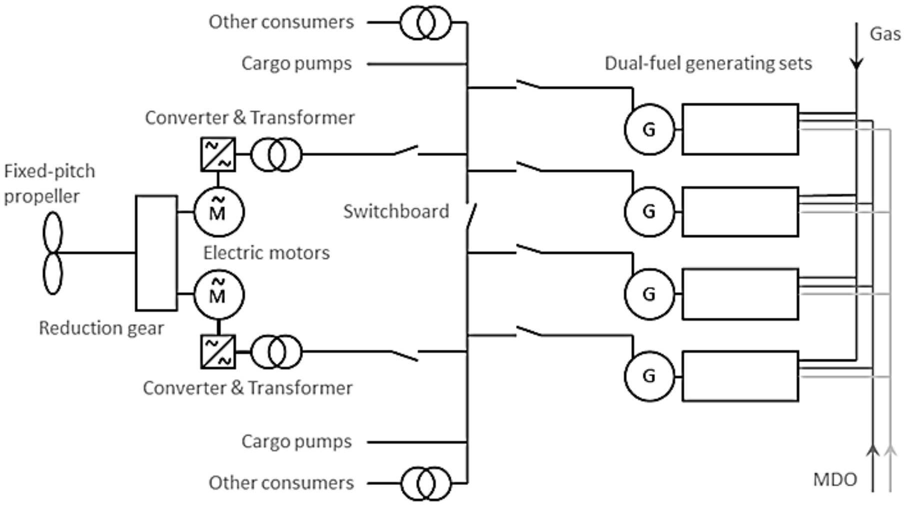


Fig. 5. Diesel electric propulsion plan.

Efficiency of medium speed diesel engines claimed by manufacturers is in the range η_e= 0.45-0.48. Despite relatively high thermal efficiency of dual fuel engines, the complexity of propulsion system results in additional losses associated with the conversion and transmission of the energy. The losses of the components are shown in Table 2. The efficiency of drive system, considering all losses is approximately η_{DE}= 0.39.

Table 2.
Efficiency of presented propulsion plants including losses of main components

PROPULSION PLANT EFFICIENCY											
CST		**Reheat Steam Plant**		**DRL**		**DF SSD-MEGI**		**DFDE/TFDE**		**COGES**	
Boilers	0.9	Boilers	0.92	2s Engine	0.48	2s DF Engine	0.517	4s DF Engine	0.47	Gas Turbine	0.46
Steam turbine	0.35	Steam turbine	0.46	Shafting	0.99	Shafting	0.99	Alternators	0.98	Alternator	0.98
Gearbox	0.98	Gearbox	0.98					Trans/Conv.	0.96	Trans/Conv	0.96
Shafting	0.99	Shafting	0.99					PEM	0.98	PEM	0.98
								Gearbox	0.98	Gearbox	0.98
								Shafting	0.99	Shafting	0.99
Propulsion Efficiency	**0.306**	Propulsion Efficiency	**0.411**	Propulsion Efficiency	**0.475**	Propulsion Efficiency	**0.512**	Propulsion Efficiency	**0.420**	Propulsion Efficiency	**0.411**

Source: Own elaboration based on: Adamkiewicz A. & Grzesiak S. 2016, www.corporate.man.eu 2017, www.wartsila.com 2017

Diesel Reliquefaction propulsion plant

In 2007, the first vessels with *DRL* propulsion plant were delivered. It consisted of two slow speed diesel engines driving 2 separate propellers. The engines could only be run on fuel oil (*MDO/HFO*), this design dose not allowed for the use of *BOG* as a fuel. Due to the need of *BOG* treatment, *DRL* plants are equipped with re-liquefaction plant. Due to the low boiling point of *LNG* (about -163°C for methane), this system is highly energy consuming. From an economical point of view, *DRL* plant is only cost effective at a high gas price. As a result of gas price fall, construction of *DRL* plats have been stopped, and researches on modification of fuel supply system started, to allow engines to use *BOG* as a fuel.

The efficiency of DRL propulsion plant, claimed by the manufacturer is η_e = 0.47. However need of re-liquefaction of BOG, and power demand for it, significantly increases daily fuel consumption of the whole power plant.

Dual Fuel Slow Speed Diesel Propulsion Plant (*DF SSD)*

The two leading manufacturers of marine diesel engines, MAN Diesel and Turbo (*MDT*) and Wärtsilä, have in their portfolio dual fuel slow speed engines. The principle of operation of both engines is similar, but the fuel gas supply system differs from each other. Ignition of air-fuel mixture is initiated by the injection of pilot fuel oil (*MDO/HFO*).

In 2016, first LNG carrier equipped with *MDT* dual fuel slow speed diesel engine, which propulsion plant and gas supply system is shown on Figure 6, was commissioned. The propulsion plant of the 178000 m^3 capacity vessel consist of two engines 5G70ME-GI, each driving a separate propeller. Main engines are supplied with gas under pressure of 150-300 bar, depending on engine load. Engines can be operated in three different fuel modes: *Fuel Mode* – combusting fuel oil only (*MDO/HFO*); *Gas Mode* – mainly gas fuel with injection of pilot fuel oil (3-5% of fuel demand); Share Mode – is a gas mode with pilot fuel injection between 5-50% of fuel demand.

Thermal efficiency of MEGI engine, claimed by *MDT* is η_e = 0.517. Due to the direct drive chain (shaft losses about 1%), it is assumed that propulsion efficiency will be around η_{MEGI} = 0.51 (worldmaritimenews.com (2016)).

It is estimated that fuel demand of two *5G70ME-GI* engines for a 178000 m^3 LNG carrier will be below *NBO* (Natural Boil off) in range of 0-80% engine load (for *BOR* (Boil off Rate) – 0.1-0.123%/day). In addition, the generator sets are equipped with dual fuel engines to consume excess *NBO*.

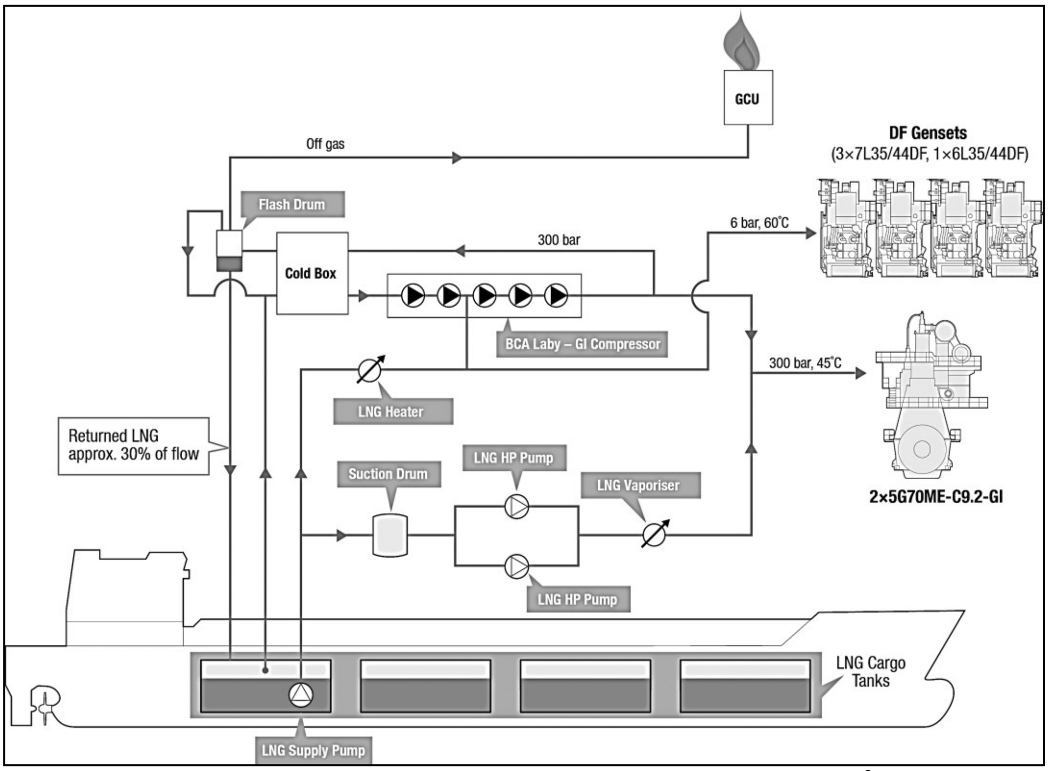


Fig. 6. *DF SSD* propulsion plant with *BOG* treatment system for 178000 m^3 *LNG* carrier.

Wärtsilä has received orders for main propulsion engines for 4 new built vessels. For Wärtsilä *xDF* design, the gas supply system uses a gas pressure of about 17-20 bar. *BOG* is supplied via electronic operated valves fitted on the cylinder liner above the scavenge pots. Gas under 10 bar pressure is supplied to combustion chamber after the scavenge phase, once intake pots are covered by the piston and exhaust valve is closed. The Wärtsilä's solution allows usage of more simple gas supply system fitted with 6-stage centrifugal compressor.

Combined Gas Electric Steam Turbine

In 2014 shipyard Dalian Shipbuilding Industry Company received from Lloyd Register Approval in Principle for gas turbine powered LNG carrier design. COGES propulsion plant (Fig. 7) developed together with General Electric, combined gas turbine with steam turbine recovery plant.

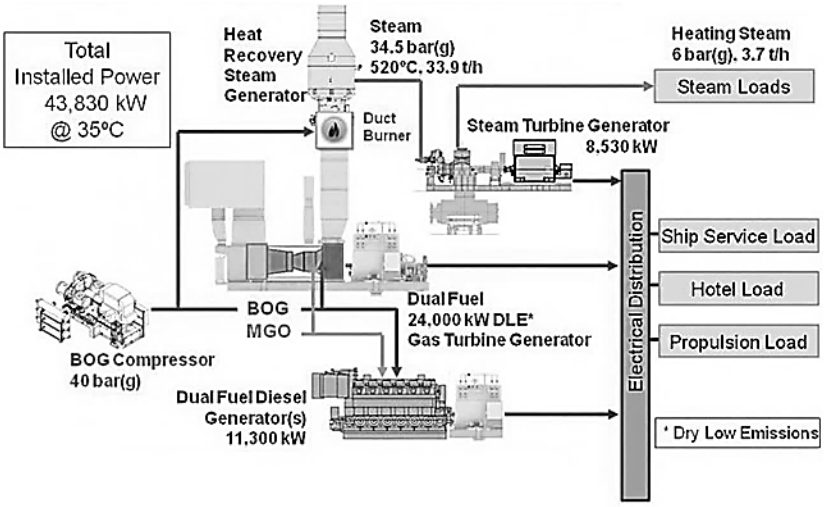


Fig. 7. COGES propulsion plant with GE dual fuel gas turbine.

In this system, the main drive unit is a General Electric gas turbine driving the propeller via an electric transmission. Steam turbine and exhaust boiler is a part of waste heat recovery system for the gas turbine. It is possible to use a mechanical drive for combined gas and steam turbine propulsion, but it complicates both the shaft speed control as well as engine room structure. It requires the use of reversible mechanical gearbox. The use of binary Brayton-Rankine cycle increases the thermal efficiency of power plant by 10% compare to gas turbine. By recovery of waste heat from gas turbine exhaust gases, propulsion plant efficiency is around $\eta_{COGES} = 0.42$.

CRITERIA EVALUATION OF ALTERNATIVE PROPULSION SYSTEMS

The main criteria for selection of propulsion plant by ship owners is the economic criterion (including fuel and maintenance costs) and ecological (emissions of harmful compounds and meeting current environmental requirements). Analysed alternative propulsion plants of modern *LNG* carriers have been confronted against conventional steam turbines (*CST*). The analysis of shipyard order books shows that the most efficient plants are most commonly ordered (Table 2). Furthermore these plants represent low CO_2 emission (Table 3).

Table 3.
***CO_2, NO_x, SO_x* emission of presented propulsion plants**

Propulsion system	NO_X	SO_X	CO_2
	[g/kWh]	[g/kWh]	[g/kWh]
CST (*50/50 BOG/HFO*)	1	11	900
Steam Reheat (*GAS ONLY*)	1	0	500
DRL (*HFO*)	17	7.7	580
DF-SSD MEGI (*BOG*)	10.1	0.88	446
DFDE/TFDE (*BOG*)	1.3	0.5	480
COGES (*BOG*)	2.5	0	480

Source: Own elaboration based on: Adamkiewicz A. & Grzesiak S. 2016, www.corporate.man.eu 2017, www.wartsila.com 2017

Table 4 shows the statement of main criteria of propulsion plants in relation to conventional steam plant. The analysis shows that plants equipped with dual fuel slow speed engines meet most of the current requirements for *LNG* carrier propulsion. At present time, due to the fact that it is relatively new technology in maritime use, their reliability is not confirmed. However, the redundancy of the prime mover has been made by the use of twin-screw propulsion powered separately by two main engines. The main disadvantage of *DF SSD* system is need of additional system (*EGR* – Exhaust Gas Recirculation or *SCR* – Selective Catalytic Reduction) to reduce NO_x emission, for both fuel oil and gas mode.
DFDE/TFDE propulsion plants have been in operation for over a decade. They are relatively high efficiency (*CST<DFDE<DF SSD*), but require as well treatment of exhaust gases to meet NO_x TIER III requirement when operating of fuel oil. In addition, the maintenance costs of this plant due to quantity of units are relatively high. The operator experience shows that reliability of diesel electric plant is significantly lower than that of steam turbine plant.
In spite of low emission of air pollutant in exhaust gases from conventional steam plants, the emission of CO_2 is much higher than in other options, due to low thermal efficiency of the plant. The other benefits such as reliability and low maintenance costs can't compensate the fuel consumption and CO_2 emission.

Table 4.
Statement of main criteria of presented propulsion plants

	Environmental Compliance	Thermal Efficiency	Fuel System	Reliability	OPEX
Steam Plant	1. Meets Tier III (gas mode) 2. SCR required. for TIER III (FO mode) 3. High CO2 emission	η_{CST}= 0.30 η_{reheat}=0.41	3 fuel modes: Gas only Dual fuel(any ratio) FO only	High Low redundancy	Low High Fuel costs
DFDE/TFDE	1. Meets Tier III (gas mode) 2. SCR for TIER III (FO mode)	η_{DE}= 0.42	2 modes: Fuel only Gas mode (min load 10% +1% pilot fuel)	<Steam plant High redundancy	High Engine maintenance costs
DRL	1. EGR or SCR for TIER III (FO mode) 2. Scrubber or LS Fuel for SECA regions	η_{DRL}= 0.47	No gas burning (min load 10% +3-5% pilot fuel)	<Steam plant propulsion redundancy	High Engine maintenance costs
DF SSD	1. EGR required for TIER III 2. Low CO2 emission	η_{MEGI}= 0.51	FO only(MDO/HFO) Gas shear mode	Unknown propulsion redundancy	High Engine and compressors maintenance costs
COGES	Meets TIER III (gas mode or MDO)	η_{C}= 0.41	FO only (MDO) Gas burning (3-5% pilot fuel)	Not proven for LNG carriers	<DFDE >Steam plant

Source: Own elaboration based on: Adamkiewicz A. & Grzesiak S. 2016, www.corporate.man.eu 2017, www.wartsila.com 2017

SUMMARY

The analysis of shipyard order book shows that DFDE/TFDE is the preferred option by ship owners at the moment. This is due to the fact of significantly higher thermal efficiency over conventional steam plant. Secondly at the moment the charter rate on spot market for that option is higher than for steam plant. Equally important is the emission of harmful components such as NO_x, SO_x and CO_2. Analysing order book and characteristics of alternative propulsion plants, *DF SSD* plant is assumed to be the preferred propulsion option in the near future. This has been assumed due to high thermal efficiency, low CO_2 emission and simple drive chain. This design as a combination of few other plants gives high operation flexibility regarding *BOG* treatment. The place for improvement remains the NO_x emission.
Due to the fact of low thermal efficiency and high CO_2 emission, conventional steam plants are gradually being replaced by alternative propulsion options. However, these solutions are not able to compete with steam plants in terms of reliability and maintenance costs, as confirmed by operational data. The latest design of steam plants (*ART, UST*) are able to compete in

terms of efficiency with plants equipped with medium-speed diesel engines (*DFDE/TFDE*) but are still less efficient than plants with slow speed diesel engines (*DRL/DF SSD*). Because of its many advantages, steam systems remain the preferred option for some ship owners to operate in a long-term charter where the main criteria remains the reliability to maintain a stable gas supply chain for the project.

Efforts of turbine manufacturers should focus in the future on improvement of efficiency of the steam plant cycle and its components in order to become more competitive. Further development and research should focus also on the improvement of gas supply systems to reduce the response time for load changes, so the boilers will be able to run safely on gas mode during manoeuvres and cargo operations.

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