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The retrofit of existing ships to natural gas operation

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Abstract

Today's world merchant fleet accounts to about 49 000 vessels, trading around the world, therefore, sailing mainly from Asia to Europe and USA, therefore, remaining most of the time away from the coasts. The UE and the USA are advancing stricter emissions regulations and declaring emissions controlled areas most of their coasts. From all types of ships, the ones operating along the coasts would be the first candidates to be converted, in particular attending to the price of alternative emissions complying fuel cost (diesel oil) and their need to comply with the imposed emissions regulations. This is true while natural gas prices are kept under acceptable commercial values, and the cost of conversions are within reasonable limits, otherwise, the investment in converting existing ships to natural gas operation, can result in a scrap of many of these ships, originating a sustainability and environmental problems if the carbon footprint of the whole process is considered. This not to mention the loss of shipping companies and jobs associated. The conversion of existing ships to Dual Fuel operation becomes a technology as well as a mindset challenge of all the players, as it requires the admissions of new technology players, as well as the acceptance from the classification societies of those players' solutions. In this paper, it is outlined as a possible conversion project path. On this paper, only four-stroke engines are addressed.

Keywords: LNG ship conversion, Dual fuel conversions, Engine emissions, Energy efficiency.

Introduction

European marine transportation is in great extent characterised by small to medium size vessels of all types and up to 15000 DWT. These vessels are fundamental to transhipment activities, transporting cargo from hubs ports to the other European ports, of which many are inland ports. Therefore, these ships are in fact the natural candidates to become LNG consumers.

These ships operate most of the time inside ECA and SECA areas, and are relatively new and equipped with four-stroke diesel engines, which may be adequately converted to dual fuel operation at acceptable cost, allowing the economic viability of the conversion project, and therefore avoiding scrap due to environmental obsolescence dictated by the environmental regulations in power.

In January 2013, 20 per cent of all seagoing merchant ships were younger than 5 years, representing 40 per cent of the world's deadweight tonnage (see Figure 1). New container ships are on average three times the size of those built 20 or more years ago, and only 5 per cent of the container ship tonnage is older than 20 years. Oil tankers, too, tend to be replaced relatively early; only 4 per cent of the existing oil-tanker tonnage was built more than 20 years ago. The average age (per ship) in January 2013 was for container ships (10.8 years) and dry-bulk carriers (9.9 years).

Country grouping Types of vessels		*0–4 years*	*5–9 years*	*10–14 years*	*15–19 years*	*20 years and +*	*Average age (years) 2013*	*Average age (years) 2012*	*Percentage change 2013/2012*
COUNTRIES WITH ECONOMIES IN TRANSITION									
Bulk carriers	**Ships**	29	13	7	13	39	15.64	18.68	-3.04
	Dwt	31	11	7	13	38	15.07	18.16	-3.09
	Average vessel size (dwt)	45 120	35 203	43 734	42 427	40 694			
Container ships	**Ships**	13	3	17	30	37	18.20	17.27	0.93
	Dwt	30	4	15	26	25	14.59	13.66	0.94
	Average vessel size (dwt)	27 602	13 760	11 201	10 566	8 560			
General cargo	**Ships**	4	4	1	7	83	30.33	29.65	0.68
	Dwt	7	7	2	10	74	26.39	25.97	0.42
	Average vessel size (dwt)	6 144	6 124	5 299	4 403	2 985			
General cargo	**Ships**	17	14	5	5	60	22.69	22.88	-0.18
	Dwt	34	34	17	6	9	9.46	8.89	0.57
	Average vessel size (dwt)	48 168	58 518	81 964	31 915	3 636			
Oil tankers	**Ships**	7	5	3	5	80	28.57	27.92	0.65
	Dwt	18	13	3	3	63	21.88	21.27	0.61
	Average vessel size (dwt)	3 378	3 655	1 237	815	916			
Others	**Ships**	8	6	3	6	77	27.92	27.49	0.42
	Dwt	27	22	11	9	32	14.96	15.46	-0.50
	Average vessel size (dwt)	23 192	25 073	26 839	8 930	2 758			
All ships	**Ships**	8	6	3	6	77	27.92	27.49	0.42
	Dwt	27	22	11	9	32	14.96	15.46	-0.50
	Average vessel size (dwt)	23 192	25 073	26 839	8 930	2 758			

Source: Compiled by the UNCTAD secretariat, on the basis of data supplied by Clarkson Research Services.
Note: Propelled seagoing merchant vessels of 100 GT and above.

Figure 1 - Age distribution of the world merchant fleet, by vessel type, as of 1 January 2013

Based on these facts, it is easily concluded that all those ships operating in the European coast, North American coasts, and elsewhere the ECA and SECA areas exist are candidates to become converted to NG operation.

While transoceanic ships sail most of the time away of Emissions Controlled Areas, and that those may accommodate a scrubber, in most ships operating doing the transhipment of cargo from the hub ports to other ports tend to operate most of their time at sea inside the Emissions Controlled Areas. For these last group of vessels, natural gas may be the natural solution, to avoid their obsolescence, and end, either for scrapping or for operation in geographical areas where emissions restrictions are not in power, as world trade perspectives are not favourable to the replacement of such vessels by new ones operated with natural gas.

The process of converting these vessels, needs to be carefully evaluated as there are a number of constraint variables to consider in first hand, namely: Cost of the conversion, Time required for conversion, Availability of natural gas in the ships area of operation, gas bunkering Logistics, expected extended life of the ship, alternative concurrent technologies such as exhaust gas scrubbers, available space on board for gas fuel tanks and bunkering station, adaptability of the ship general arrangement.

As it can be realised, such a project needs to be implemented in a very efficient way, therefore extremely careful planning of the project details and steps need to be put in place in front.

These projects have typically a number of difficulties. While, some major engine manufacturers may offer their conversion services for some engine models, offering a package that includes all the project engineering including the conversion kits, it may happen that they may not be interested in to offer their conversion packages to convert some engine models, therefore pushing the shipowner to a difficult position, eventually a ship reengaging, a ship stop, or a scrap decision. Space availability on board to accommodate the LNG tanks, and finally, the acceptance from the classification societies of the conversion operated over the main engines and alternators performed by other companies other than the engine manufacturers.

The bigger parcel of converting a vessel to gas fuel operation rests with the main and auxiliary engines conversion to gas fuel operation, and gas fuel system, but also eventual loss of cargo space. Existing diesel engines can be converted easily to dual fuel operation, in fact, the wisest option, as in case of lack of gas fuel, or excessive price (despite it is not foreseeable), the ship is still operational. So, diesel oil is used as ignition fuel but serves as a backup fuel in case the gas fuel system becomes inoperative for any reason. Also, gas-fuelled engines tend not to behave in transients as types of diesel, therefore diesel oil is used throughout the manoeuvring operations.

Main difficulties associated to existing vessels conversion to natural gas operation

As mentioned above, only four-stroke engines equipped with natural gas are considered in this paper. The main difficulty has a financial nature that is to know if the remaining life of the ship is sufficiently long to recover the investment on the conversion, and also to predict the natural gas cost during the operational life of the project. Knowing those variables, all the other ones are technical and can be solved.

The main group of candidate ships to be converted are the ones that are relatively new, and which operate most of the time, inside emissions controlled areas (ECA's) where natural gas will be available for refuelling in a near future. Although fuel availability may be a problem today, it is a logistics problem that is under solution all across Europe. The conversion project needs to consider:

- Economic viability of the project;
- Technical feasibility;
- Class rules and regulations;
- IGC code compliance.

Local traffic vessels (Figure 2) and ferries are two types of strong candidates to natural gas operation. These vessels, depending on their size may be operated with compressed natural gas, as this may be a cheaper solution and less complicated bunkering operation. Gas storage in the form of LNG is considered the most attractive alternative due to the high energy density of LNG and, as a consequence, the relative compactness of the gas tanks required.

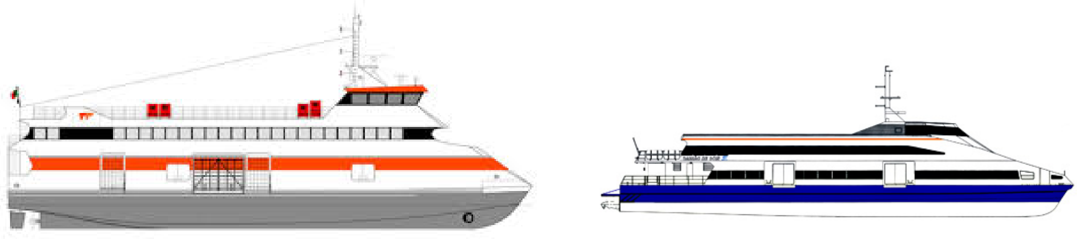

Figure 2 - Local traffic ferries candidates to CNG.

However, there are many other vessels, such as handy size container vessels, small chemical tankers, small bulkers, and RoPax that are potential candidates to be converted to LNG operation.

Economic viability of the project and environmental considerations

The economic viability of a conversion project has various variables that need to be addressed before its initiation, namely, the cost of gas (about 39% less for equivalent energy based on IFO380 but varying), the expected remaining life of the ship, so has recovery of the invested capital can be achieved. Cost of the conversion of main engines, any possible loss of cargo space due to the gas tanks needs also to be addressed. The gas storage space and weight are influenced in some way by the technology involved, gaseous CNG of liquid gas LNG, and this may also impact on the ship stability. Gas fuel piping pressures have also a strong impact on classification rules and cost. Gas availability and its origin, ship area of operation and gas availability, gas cost forecast and its stability, are just some of the variables that need to be clear before the project initiation.

Regarding the environment considerations, the use of NG as a propulsion fuel, has the following considerations, cleaner combustion gases in terms of Sulphur Oxide (SOx) (SOx emissions 95% lower than ECA limits), Particulate Matter (PM) (PM emissions may be as lower as 95% when compared with IFO180 operation),Nitrous Oxide (NOx) (NOx by almost 100%), but exhaust gas emissions from reciprocating engines are highly pollutant in what refers to the methane volatile organic compounds (VOC's) due to gas slip, and as a result of manoeuvring and other operations gas fuel systems need to purged and vented releasing to the atmosphere considerable quantities of methane that is extremely aggressive to the Ozone Layer. In the near future, catalysts or flares will be considered to oxidise the purged and vented natural gas, becoming a potential extra cost in the near future.

Technical feasibility. Major areas of intervention.

The use of natural gas as a fuel for propulsion of existing ships, requires a number of modifications that are originated by gas storage gas, fuel system layout and refuelling safety, liquid spill risk prevention, explosion prevention, ship energy availability and control engineering of operation, and all that need to be addressed at an early stage. Laser scanning can be used at this stage with advantage of time and accuracy to define spaces and volumes available on board.

Gas storage operation safety includes all aspects of concerning: Tank type and its location, on board, considering anti-collision safe distances from hull sides, and ship stability implications;

Ventilation of spaces: Protection of ship hull and accommodation structures from liquid gas spills and explosion containments;

Fuel gas system layout: distribution and respective emergency cut off arrangements, to the various equipment's including gas fuel control equipment such as cold boxes, gas skid (regulators, PSV's, flowmeters, pressure transducers, filters, etc.) and gas fuelled consumers;

Type of piping and respective materials: single or double wall piping, gas piping venting and purging arrangements, and gas handling systems like filters, flowmeters, manual isolating valves;

Type of gas technology to be installed on board the engine: injection system to be used, Single point fumigation (gas fumigation before turbocharger), or Multipoint port injection system (only four-stroke engines are considered here), are the only candidates for the conversion, in particular, the later one as its gas slip is much lower than the first.

Figure 3 illustrates an example of the project spiral, of a conversion of a ship to dual-fuel operation (diesel oil and Natural gas). In these cases, existing diesel engines may be converted into dual fuel engines by installing a multi-point port injection system, typically with a gas fuel pressure on top of the engine around 6 bar (low pressure system). The engines receive also monitoring & safety systems such as knocking a misfiring detection, control system, and even a dashboard for engine operation. With this solution, existing diesel engines may reach levels of fuel

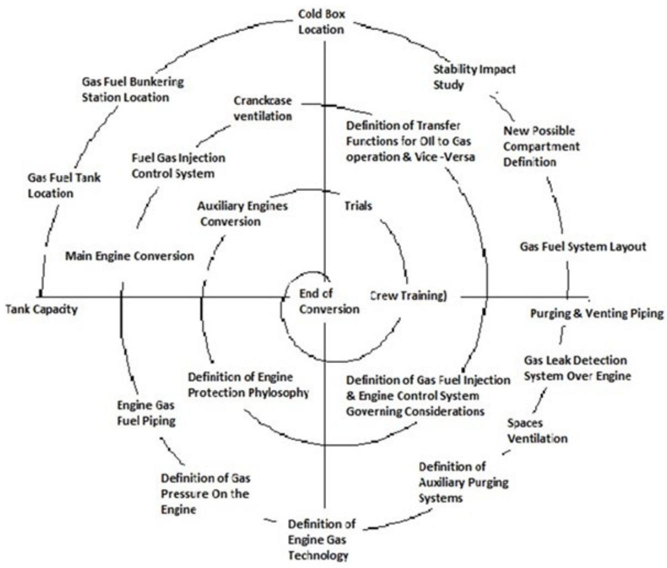

Figure 3 - Project Spiral of a Ship Conversion to Dual Fuel.

substitution ratios in the order of 95% (95% of the energy required per cycle is released by the gas, and 5% of the energy from the diesel oil as ignition fuel).

In terms of cost distribution, it varies typically as follows:

- Automation and control systems: 10%
- Project Management, surveys, integration engineering, naval architecture: 15%
- Main engine conversion and auxiliary systems components: 15%
- Workmanship and shipyard: 29%
- Fuel gas system (LNG tanks, Cold box, Piping and process equipment): 31%

Some considerations concerning existing diesel engines to be converted.

When starting such a conversion project, assuming that all gas logistics' problems are solved, a number of options need to be taken at a very early stage, and namely, the minimum required fuel gas pressure on top of the engine, as this variable has a strong impact on the complexity of the conversion. By definition low pressure gas systems are those that operate at a pressure lower than 10 bar and high pressure would be all the gas systems operating with gas pressure equal or higher than 10 bar. In fact, for most of the conversions of existing four-stroke diesel engines to dual fuel operation, either of pre-mixed type (where fuel gas is pulverised before the turbocharger at very low pressure) or a Multi-point gas port injection valve, the use of low pressure gas fuel systems will do.

The reason to consider as a first option a low pressure system is that, the maximum gas pressure needs to be just the sufficient to avoid the gas valves choked flow condition, therefore, gas pressure needs to be at least 1.3 times the air pressure at the air manifolds, i.e., after air coolers.

One note may be of practical use, and that is related with the option of using pre mixed fuel gas fuel engines and conversions, which have a poorer efficiency, are more pollutant as cylinders are scavenged with a mixture and are more prone to air and exhaust gas trunking explosions, than the multipoint port injection engines.

Main modifications of engines

Transient response

The engine control system must be designed in such a way, that transient response characteristics of dual fuel engines are to be appropriate for the intended application. Dual fuel diesel engines (gas mode) driving generators need to satisfy the performance criteria defined by ISO 8528.

Starting Air

Where air is introduced directly into the cylinders for starting purposes, the starting air branch pipes of each cylinder need to be fitted with flame arresters, as some gas may be inside the cylinders and explode.

Air Intakes

When air intakes are located inside the engine compartment, these are to be situated as far apart as practicable from the gas fuel supply pipes such that, in the event of a gas leak, the risk of the gas entering the intake is minimized. Engine air intakes located outside the engine compartment are to be lead from a non-hazardous area at least 1.5 m away from the boundaries of any hazardous area.

Air Inlet Manifolds

Explosion relief valve need to be fitted into the air inlet manifolds. The arrangement and location of the protection devices like rupture disks is to be such as to minimize the dangers to personnel and equipment from operation of the protective device.

Protection of Crankcase & Explosion Relief Valves

The explosion relief valves need to be fitted in way of each crank throw.

Ventilation

In case one or more engines exist, their crankcase ventilation pipes must be independent to avoid possible spread of fire to the other engines. Also, the crankcase is to be continuously vented but not producing a fresh air flow within the crankcase.

Crankcase ventilation pipes are to be as small as practicable, to minimize the inrush of air after a crankcase explosion. If a forced extraction of the oil mist atmosphere from the crankcase is provided (for mist detection purposes for instance), the vacuum in the crankcase is not to exceed 2.5 × 10-4 N/mm2 (2.5 mbar).

The outlets of the vent lines need to be in a non-hazardous area in the open air and equipped with a flame arrester.

Inerting

For trunk piston dual fuel engines (as well as for other gas engines), means of inerting and aerating the crankcase before opening the crankcase doors for maintenance must be in place, and a gas sampling connection must be available to measure the gas concentration through a portable gas detection equipment.

Instrumentation

The crankcase is to be protected by an explosion proof approved oil mist detector must be installed.

Protection against Explosion

A Failure Modes and Effects Analysis (FMEA) needs to be carried out, to identify all plausible scenarios of gas leakage and the resulting possible explosion.

Engine Exhaust System
Explosion Protection

Explosion relief valves or other appropriate protection against explosion, such as burst discs of an approved type, need to be installed on the exhaust manifolds. The arrangement and location of the protective devices is to minimize the dangers to personnel and equipment from operation of the protective device, namely orientation in a safe direction away from personnel.

Installation

The exhaust gas pipes from dual fuel diesel must be independent so the spread of fire from one engine to another is difficult and exhaust pipes sloped upwards after the turbocharger in order to avoid formation of gas pockets.

Purging

In the event that a dual fuel engine stops during the gas fuel mode of operation, the exhaust system is to be purged for a sufficient time, to clean out the gas that may be present. The purge time is to be based on a minimum of four air changes of the volume of the exhaust system, and may be done by using a fan.

Auxiliary System Venting

Means of purging auxiliary system circuits, such as cooling water or dry/wet sump lubricating oil systems, that are likely to contain gas in normal conditions or abnormal conditions as a result of a component failure are to be arranged in such a way that may be vented out to a safe location external to the machinery space and to be fitted with a flame arrester.

Control and Monitoring Systems

The engine control system has three functions:

- Check whether the conditions for start and operation are assured, including self-testing;
- Control the gas injection, and preparation;
- Control the safe operation of the engine itself in Dual Fuel node, by adjusting the quantity of gas (through gas pressure inside the common gas rail, gas injection valve timing and angle of injection),

and diesel oil at each moment. By monitoring the operational parameters of the engine such as, engine load, angle of ignition of the cylinder charge, knocking, misfiring, pre-ignition, temperatures, etc. Figure 4 represents the human machine dashboard.

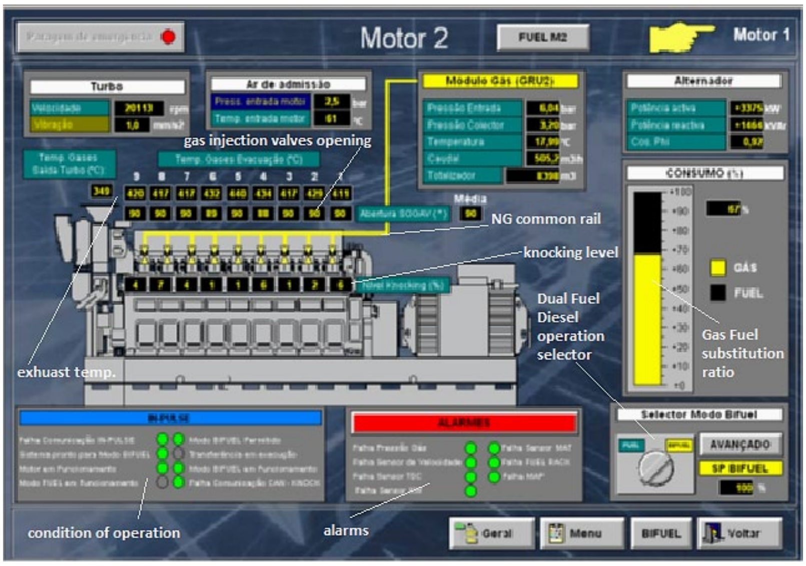

Figure 4 - Human machine interface

The engines operation is controlled from the interface created, including alarms monitoring, as well as advanced manual adjustments protected by password (like injection valve timing).

i) The changeover of fuels, was accomplished either by manual action by the operator (engine control room, or bridge); by pushing the button "Dual Fuel Diesel Operation Selector" or in an emergency, automatically decided by the safety control system. The engines were capable of continuous operation using the alternative fuel supply without interruption of operation.
ii) Changeover to and from gas fuel operation is possible at a power level and under conditions where it can be done with acceptable reliability and safety. On power reduction the changeover to oil fuel is fully automatic.
iii) Only oil fuel is used to start the engines and prior to a normal stop, or when operation in gas mode becomes unstable or uneconomical. On normal stop as well as emergency shutdown, gas fuel supply is shut off before oil fuel. In case of shut-off of the gas supply, the engines were capable of continuous operation by oil fuel only developing their full power.

Table 1 - Monitoring and Safety System Functions for Dual Fuel diesel engines

Monitored Parameters	Alarm	Automatic Activation of the Block and Bleed Valves	Automatic Switching Over to Oil Fuel Mode (1)	Engine Shutdown
Gas fuel supply systems – malfunction	X	X	X	X
Pilot oil fuel injection – malfunction	X	X	X	X
Exhaust gas after each cylinder, temperature – high	X	X	X	X
Exhaust gas after each cylinder, deviation from average, temperature – high	X	x	X	X
Cylinder pressure or ignition – failure, including misfire and knocking	X	X	X	X
Bearing shell temperature 5^{o}C above average normal full load	X		X	
Failure of the control-actuating medium of the block and bleed valves	X	X	X	X
Oil mist in crankcase, mist concentration	X	X		X
Failure of the control-actuating medium of the gas valves, as applicable	X	X	X	X
Failure of the gas valve oil sealing system, as applicable	X	X	X	X
Engine stops – any cause	X	X		X
Oil mist in crankcase, mist concentration	X	X	X	X
Gas pressure-Air boost pressure<1.5 Gas pressure	X	X	X	X
Pmax > Nominal Pmax			X	
RPR>6Bar/^{o}	X		X	
Knoking (after 3rd entative)	X		X	
Early cylinder ignition (pre-ignition)	X		X	
Any failure of gas sensing system	X	X	X	

Engine conversion experience

TecnoVeritas has been providing engineering consulting services to many organizations, as well as diesel engine conversions worldwide since 1999. Included are some of the major engine makers and engine sizes. A range of in-house developed technology solutions for engine monitoring, control, and operational optimisation have been developed. Figure 5 shows the project where two Wärtsilä 9L32 diesel engines converted to dual fuel operation on heavy fuel oil and natural gas, and describe technological solutions chosen as well as operational data from the engines. Each of the two 9L32 diesel engines Wärtsilä had approximately 96,000 hours of operation on heavy fuel oil (HFO). The objective was to convert these two IFO380 engines to use as much natural gas as possible without endangering the engines operation. The quantity of gas and fuel had to be carefully controlled, to avoid mechanical stress higher than that created under normal HFO380 operation. For that, a thorough techno-economic calculation was carried out, as well as a pre-

Figure 5 - View of the two engines 9L32

assessment of engineering key points. Then a proper engines signatures were taken, cylinder pressure open diagrams (to study the maximum rates of pressure rise) turbocharger speeds, as well as cylinder vibration frequencies. Simultaneously, the specification of operation software, as well as the monitoring and safety software was performed, originating an appropriate human engines interface.

Fuel injection system

Gas fuel port injection valves (see Figure 6), were controlled by an injection controller receiving information from various sensors and systems installed on the engine, from the gas regulating unit and from the process controller (see Figure 6). The original mechanical controller was replaced by a hydraulic actuator controlled by the main injection controller allowing in this way the transfer of diesel to dual fuel mode and vice versa. The injection of the correct quantity of gas during the induction stroke, after the closing of the exhaust valve and before the closing of the inlet valve is continuously adjusted via the injection angle and gas pressure on the common rail of gas (yellow thick pipe on engine top), therefore allowing a fine adjustment of the gas energy per stroke. The system allowed the control of the gas quantity individually therefore offering a high flexibility in what concerns the engine operation. The gas fuel injection system was continually monitored via the KDS (knock Detection System developed by TecnoVeritas). The KDS system includes one accelerometer per cylinder identifying in each cycle the knocking frequencies, or the absence of combustion (misfiring). In any one of these conditions alarms and commands are originated immediately to reduce the load to a particular cylinder or to all of them or even transferring the engine operation from Dual-fuel to diesel.

Figure 6 - Injection controller & Gas injection valve

Conclusions

Existing ships in fair condition (hull and Machinery) operating inside the ECA areas, will be pushed out of market due to exaggerated diesel oil costs of operation;

The conversion of existing ships to dual fuel operation, it is a sustainable environmental practice, that can reduce the carbon foot print into two ways, the operation of such converted ships will emit about 1/3 less of carbon dioxide, and the avoided emissions due to scrapping and recycling of the materials;

By converting the existing engines to dual fuel operation, there will be no need to change gearboxes and or propellers, therefore the project may become more cost contained;

An engine power reduction on dual fuel mode will be noticeable, only for engine loads where cylinder charges energy contains more than 50% of energy based on gas fuel and at loads above 50% MCR;

Engine maintenance costs, and lube oil costs will drop, as engine will run much cleaner than with HFO;

The use of LNG or CNG depends on the vessel operating profile, being cheaper the CNG storage system in comparison to the LNG system;

The capacity of the LNG tanks, has a strong impact on the cost of the tanks, therefore they should be as smaller as possible, and if possible of standard size.

If the LNG tanks are to be located outside, the rules of classification may be less restrictive, resulting in cheaper solutions;

Gas fuel distribution system should be of low pressure, ($P_{gas} < 10$ bar), therefore resulting in less restrictive rules and therefore in a cheaper system;

The conversion project must be comprehensively developed, being extremely important the preparation at the design office starting with the specification of materials, ship interiors, prefabrication of parts, such as piping, ventilation trunks, automation, etc.

The obtaining of an agreed LNG price at an early stage with one or several gas suppliers, would remove the project economic calculations uncertainty and will increase significantly the success probability of the project;

Classification societies should be opened to classify as appropriate not only the engine manufacturers trademark, but as well as other dual fuel components makers, therefore making possible existing ships to become LNG operated, contributing for the employment of people at sea and ashore.

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