Concept design and feasibility study of propulsion system for yacht: innovative hybrid propulsion system fueled by methanol

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***Abstract*— The Marpol Annex VI Reg.13 entered into force in 2016 imposes severe limitations on the NO_X emissions of ships, getting the most stringent standard to date ("IMO Tier III").**
These are enforced in the Emission Control Areas (ECAs): US waters on both Atlantic and Pacific coasts, in the Hawaii region and in the US Caribbean (Puerto Rico) area. More ECAs (e.g., Mediterranean Sea, etc.) could be added soon. Among the solutions to comply with IMO Tier III, hybrid system is that seems more encouraging specially when supplemented by battery and fuel cells.
The paper deals with a concept design and feasibility study of the propulsion system for a yacht of 80 m in length with a conventional diesel electric configuration integrated with fuel cells and battery plants which consent for further operations inside ECAs where fuel cells are used as means of power generation. The hydrogen required for fuelling fuel cells is obtained by a methanol reforming system installed on board as well.

Keywords— Fuel Cells, hybrid propulsion, methanol. maritime applications

INTRODUCTION

With an increasing demand to develop more efficient and cleaner ships, hybrid technology has drawn attention from the marine industry. Thanks to the breakthrough in battery technology which can improve the flexibility of selecting power sources, the last few years showed several developments in hybrid mega yacht ship propulsion [1].

Mega yachts compliance with IMO Tier III by four possible solutions:

a) the engine exhaust is fitted with a dedicated filter, performing a Selective Catalytic Reduction (SCR); urea is used to reduce NO_X content of exhausts to acceptable levels;

b) SCR filters are fitted on some engines; the flexibility of the hybrid configuration allows for building and operational cost saving;

c) using a dual fuel propulsion system (DF), the liquified natural gas (LNG) can be used in ECAs instead of marine diesel oil; significant reduction in emissions is obtained;

d) using a conventional diesel electric configuration, supplemented by Fuel Cells (FCs), allows for extra-clean operation inside ECAs when FCs are used as the sole means of power generation.

In the case of SCR dedicated filters (a) main advantages are the proven design, the low installation costs and the easy application on board. Disadvantages deal with extra auxiliaries to be installed in the engine room (arrangement & space constraints) and the exhaust backpressures to be closely monitored, especially when additional particle filters are also installed.

In the case of (b), advantages are the high operational flexibility, SCR filters can be installed on gensets only, fast speed can be reached with a less powerful main engine and with overall reduced costs, and all engines mostly operate at their highest efficiency. Disadvantages dealt with the slightly more complicated propulsion chain & propulsion management which require more space and weight: e.g. an additional reduction gear if compared to conventional diesel-electric and additional generators power if compared to conventional diesel-mechanical.

Installation of DF with an electric propulsion has many advantages: very clean exhaust emissions in LNG operational mode, design and installation are now covered by recently published dedicated rules and regulations; expected reduction in operational costs (reduced fuel cost, better energy recovery) and flexible and silent electric propulsion. The main drawback is the LNG tanks arrangements and the not fully developed land-based LNG supply chain. At the basis of the design or the refitting of a new ship, there is a market analysis assessing the feasibility of an estimated investment.

For pleasure crafts less than 24 m Italy is second only to Holland, while, concerning the yachts over 24 meters in length, the primacy is of the Italian shipyards, collecting 46% of world orders, according to Global Order Book, followed by USA (19%), Holland (14%), Turkey (9%), United Kingdom (8%) and Germany (4%) [1].

Travel destinations are various, the most popular area is the Western Mediterranean. The choice of remarkable conditions, such as polar ones, is growing interest considerably. Global warming, and the resulting melting of ice pack, has made such extreme regions more and more accessible, so an increasing market is now open, leading to Mega Yachts designed to withstand rough weather conditions of these areas.

At the EU level, the European Commission set out a strategy in 2013 to integrate the mitigation of maritime emissions into the EU's policy for reducing GHG There are currently two ECAs in Europe, one in the Baltic Sea (SOx: adopted 1997) entered into force 2005; NOx: 2016/2021) and the second covering the North Sea, (SOx: 2005/2006; NOx: 2016/2021) including the English Channel, while the Mediterranean Sea is going to be the next ECA area in Europe emissions [2].

Options to reduce emissions are closely linked to the improving of the operational efficiency [3,4,5,6], improving ship and equipment efficiency, new ship designs, the use of alternative fuels and technologies, such as FC technology [7,8,9].

One of the most promising energy production system on board are FCs. In the maritime sector, FC power generation can significantly eliminate or reduce NO_x, SO_x and solid particulate (PM) emissions and reduce CO_2 emissions compared to conventional internal combustion engines. Further advantages of the application of FCs in the maritime sector are the reduction of noise, vibrations, their modular and flexible design, the generation of water, the possibility of operating in cogeneration, etc [10]

Currently, most vessels are powered by heavy fuel oil (HFO). This is a cost-effective but polluting fuel, as high levels of asphalt, carbon residues, sulphur and metallic compounds combined with a high viscosity and low volatility mean that HFO produces significant air pollutants and GHG emissions. MARPOL limits for levels of NO_x and SO_x, for example, and the 0.1% sulphur limit effective since January 2015 in defined ECAs precludes the normal combustion of HFO and has resulted in ships either implementing emissions abatement technologies or using alternative fuels.

The restriction on emissions can facilitate innovation on low-emission fuels. Nowadays the most used are LNG, biodiesel, and methanol.

Methanol could be a good candidate as a clean-burning marine fuel, as it produces low air pollution emissions, such as SOx and NOx, and overall CO_2 emissions in agreement with new environmental regulations from the International Maritime Organization (IMO) [11]. Methanol can be also one of carbon-neutral electro fuels when produced from hydrogen via electrolysis and CO_2 from the atmosphere, biomass or from the exhaust of industrial processes [18,19,20]. In FCs methanol can be used either directly in direct methanol fuel cells (DMFC) or indirectly via methanol reforming into hydrogen-rich gas mixture in LTPEMFC and HT-PEMFC.

Contrary to DMFCs, reformed methanol fuel cells are an efficient way of using methanol to produce energy, with up to 50% overall electrical efficiency [24,25].

A reformed methanol fuel cell (RMFC) is a HT-proton exchange membrane fuel cell that operates at temperatures above 100°C, typically between 160-180°C

The use of LT-PEMFC require a CO removal stage between reformer system and fuel cell, that has low tolerance to CO poisoning.

The higher operating temperature of HT-PEMFC comes with an added advantage of higher tolerance to impurities in the fuel compared to their lower temperature counterparts.

The IGF Code is an IMO Code expressly written for low flashpoint fuels, such as LNG and methanol, to perform the risk analysis demonstrating that an equivalent level of safety is achieved.

The growth of the methanol economy goes together with the hydrogen economy and considers the growing penetration of renewable energies around the world. Unlike traditional methods, where "black" methanol is produced from fossil sources, renewable methanol, also known as "green" methanol, can be produced from H_2 and CO or CO_2 with net zero CO_2 emissions. These processes use hydrogen from renewable electricity and CO_2 from biogas or atmospheric according to the direct conversion process of CO_2 to methanol (CTM). The main sources of renewable CO_2 are air and biomass. When methanol is not produced from renewable sources, it is called "grey" methanol [12].

In order to obtain a hydrogen rich gas able to power the FCs system, a fuel processor, also known as reformer, has to be adopted. There are several advantages in adopting a reformer on a mega yacht, the most notable being that the direct use of hydrogen into the FC system would require storage in bulky and complex tanks, with all the relevant safety hazards. There are several types of reformers according to the reactions involved and reactors used to produce H_2. For instance, the most common is the methanol steam reformer leading to hydrogen rich streams (up to 80%) [13].

The purpose of this paper is the study the integration of a FC system on board a conventional mega yacht design, coupled with a preliminary verification of the available operational profiles and the evaluation of the consequences induced on the yacht's overall configuration.

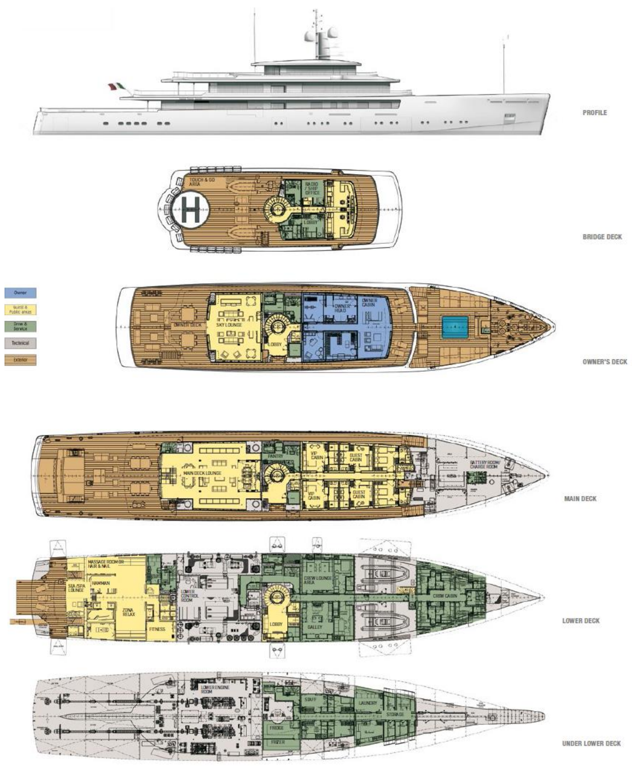
The choice of a low emission vessel – nearly zero emissions - would be not only an innovative alternative to classic propulsion, but also gives the opportunity to sail in low emission and in exclusive areas where other conventional mega yachts would not have access to (ECA).

MATERIAL, METHOD AND RESULTS

As previous underline the paper has set as target the feasibility installation of FCs on board of a Mega Yacht. Thanks to this hydrogen-based technology it is possible to install a hybrid solution on board that will provide a silent, comfortable and eco-friendly sailing. Since rules for carrying hydrogen on board are not fully developed, a hydrogen carrier has been used: methanol.

Figure 1 shows the reference mega yacht to be converted with main dimensions and characteristics synthesized in table 1; the Hotel and Service load, underway, in Summer is about 773 kWe, while at anchor in Summer is about 750 kWe.

Figure 1 reference vessel 80m Yacht Crystal Luxury from [14]



Trough the regulatory framework concerning low flashpoint fuels and FCs on board, it will be possible to develop a case study for the innovative propulsion system and four operational profiles for the vessel.

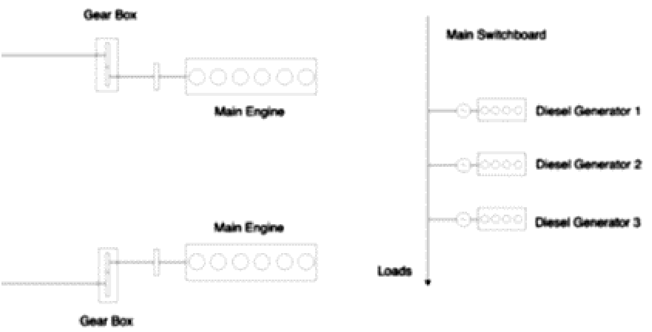
TABLE I MAIN CHARACTERISTICS OF 80 M YACHT CRYSTAL LUXURY FROM [14]

Length overall	80 m
Max beam	14 m
Max draught	4 m
Gross tonnage	4 m
N° of decks	5
Owner and guests	12+2
Suites for owner and guests	7
Captain, crew and staff	22
Propulsion engine power	2x2465 kW
Propellers	2XCPP
Cruising speed (85% Max power)	17 kn
Max speed (100% Max power)	18.5 kn
Nautical range at 12 kn	Abt. 6,000 nm
Bow thrusters	1x300 kW
Diesel generator	3x465 kWe
Hotel and Service load, underway, Summer	Abt. 773 kWe
Hotel and Service load, at anchor, Summer	Abt. 750 kWe

Propulsion system of the Mega yacht to be converted

The configuration is composed by a conventional propulsive set based on 2 main Diesel engines, 2465 kW each, connected to the two propellers. The electric power generation is separate from propulsion and is composed by three 465 kW Diesel generators. The generators have been dimensioned to supply all the on-board electrical loads with only one device running. A simplified scheme of the system is given in Figure 2.

Figure 2 Scheme of the propulsion system of Mega yacht to be converted: ME – 2x 2465 kWb; DG 3x 465 kWe



The use of the diesel engine prevails for the propulsion of mega yachts; one of the problems of pleasure vessels is the limited space available on board, so it is important to optimize the weight and volume of elements that will be part of the engine room. For this reason, fast four-strokes diesel engines are preferred which, compared to slow two-strokes, have smaller dimensions but speeds between 1000 and 2000 rpm, which is why direct coupling with the propeller is not possible, but reducer (Gear Box) is necessary to allow lower rotation speed.

The hybrid solution on board with FC technology, with no impact on the owner and guests' spaces, requires a different configuration of tanks and machinery space and plants. Subdivisions is changed a little as necessary.

B. New configuration of the propulsion system with hybrid solution

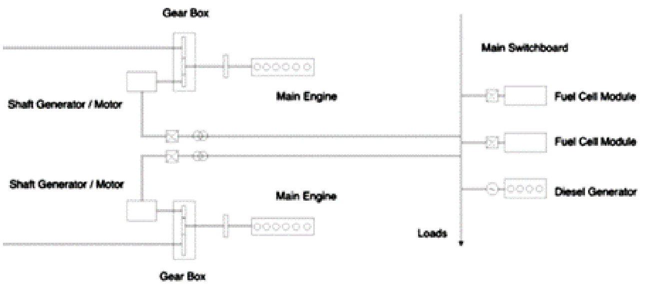
The hybrid solution to be installed uses PEMFC (Proton Exchange Membrane FC) technology with hydrogen as fuel, obtained by on-board methanol reforming. In this respect, in order to store methanol, the IGF code regulation is considered.

Since the FCs work in a DC range, an inverter is installed after each module, to convert DC in 60 Hz AC before connection to the main switchboard for the on-board loads. An AC/AC frequency converter is also needed, in order to convert the shipboard 60 Hz frequency to the one needed by the shaft motor and the other way around. This system therefore consists of diesel engines, shaft generators directly connected to the reducer in order to allow more types of operation profiles, diesel-generator, FC modules.

In this case, engines to be installed require a rated power of 1920 kWb at 100% MCR.

A simplified scheme of the power system is given in Figure 3

Figure 3 -scheme of new configuration propulsion system ME: 2x1920 kWb at 1970 rpm; FC: 2x 600 kWe; DG: 1x 690 kWe; Shaft gen/mot: 2x 500 kWe.



The FC system consists in 2x600 kW modules, light and compact provided by Powercell company, model MS-200 [15], which can independently run or stand by to keep high loads and high efficiency. System data of FC are shown in table 2.

TABLE II SYSTEM DATA BY POWERCELL MS-200

Max net power	200 kW
Dimensions	0.7 x 0.9 x 2.0 m
Volume	1260 l
Weight	700 kg
Gross Output (rated power)	600 V / 380 A
Voltage Output	Normal operation: 500-1000 VDC
Current Output	60-450 A
System heat Output	Up to 200 kW
Coolant outlet temperature	Up to 80 °C
Fuel Quality	Hydrogen ISO 14687:2019, SAEJ2719_201511 and T/CECA-G 0015 201
Fuel Inlet pressure	3-8 barg
Fuel Consumption	13 kg/h at 200 kW
Communication and control	Can Bus
System efficiency (peak, BOL)	55 %

Powercell MS-200 runs on hydrogen and can be connected in parallel to offer solutions for large power needs. In this case the units are connected in parallel to a common DC bus through DC/DC converters. Each 600 kWe module consists of 3x200 kW stacks. The exact weight/volume including BoP

depends on customer requirements, i.e. available space and system functionality. Preliminary estimate given 900 kg and 1.8 m^3 for each module with a lifetime of about 25000 hours. Several companies have been studying and producing fuel processors (FP), with a focus on light hydrocarbons and methanol [13,14,15]. Nevertheless, the literature is poor in data regarding the reformer needed when using methanol as H_2 source for fueling a PEM.
Oxidative Steam Reforming (OSR), also called Auto Thermal Reforming, can be considered as a combination of partial oxidation and steam reforming. In the OSR process, steam and oxygen are fed together as oxidants to reform the hydrocarbons or methanol into a H_2 rich fuel stream, suitable for FCs, and the heat produced from exothermic oxidation reactions is used to promote the endothermic steam reforming reactions. In case of methanol OSR, the temperature of this process may vary in a range of 180 – 225 °C.
OSR system then seems to be the best solution to be installed on the hybrid mega yacht. According to this, the product "STAR" provided by Nuvera company has been assumed as reference, such a system includes both the reforming and the clean-up section. The single reformer unit dimensions are 220x840x460 mm. To cover the power required on board (1200 kW) 24 units have to be installed for a total weight of 2t [13].
The hybrid system allows combining mechanical and electrical propulsion in the kinematic transmission. Therefore, propulsion efficiency is optimized and, at the same time, responds to a demand for variable power quickly and flexibly. The reducer gearbox provides with a power take in or take off (PTI/PTO), coupled with a 500 kWe shaft generators/motor, able to work both as propulsion motor and shaft generator. The controllable pitch propeller is maintained as on the reference ship.
The presence of the shaft generator allows using the waste energy of the engine and provides additional work to the propeller shaft when the main engine is underperformed. The shaft generator is characterized by two operating modes:

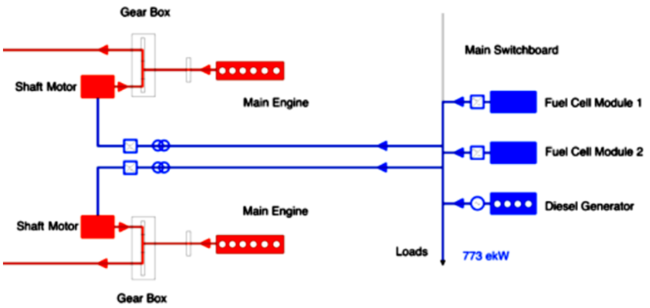
- Power Take Off (PTO): the additional energy generated in the main engine is taken by the shaft generator to produce electricity as an alternative to generating sets;
- Power Take In (PTI): the shaft generator supplies propulsion power to the shaft. In this mode, it can also be used as an emergency backup machinery to push the ship to the nearest shore if the main engine fails, thus increasing the redundancy factor.

A Reintjes solution [17] is chosen, already set up for hybrid solutions, with the electric motor able to work in PTI mode as electric motor and in PTO mode as shaft generator (WAF-RHS 873). This configuration also works in boost mode, using both the diesel engines and the FC systems in combination to drive the propeller to provide the maximum thrust. The system includes the electric motor/generator, the gearbox, the frequency converter and relevant couplings.

C.Operating modes of the hybrid solution

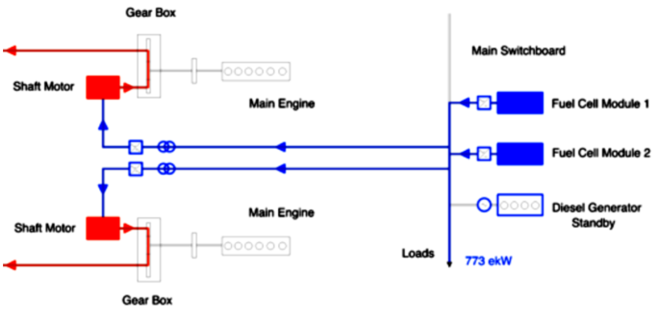
One of the advantages of hybrid propulsion, in addition to reduced consumption, is that of being able to navigate according to several operating scenarios, which are the following:
a) PTI - Booster Mode (BM): the vessel is sailing at the maximum speed 18.5 kn (6 hours of autonomy). Whitin this mode is used all the available propulsive power: the main diesel engines, the shaft generator in PTI mode, the genset unit and the FCs work in synergy to allow the ship to reach the desired speed. The hotel load and services are guaranteed by the power supplied by the FC system. Figure 4 shows the scheme of this profile.

Figure 4 Max Speed Hybrid Boost Mode; Propulsion: 2x 1920 kW diesel engines; 2x shaft motors 500 kWe; Generators 1x690 kWe diesel generator; 2x600 kWe FC modules at 100% Load.



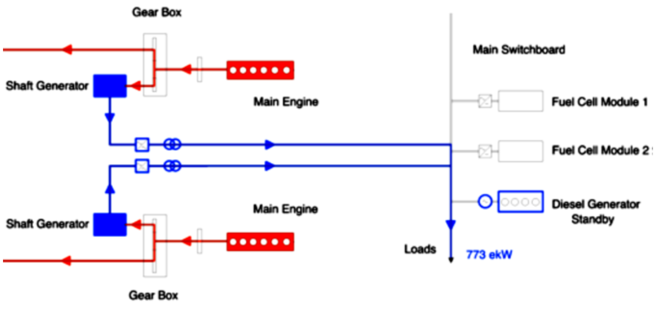
Considering a safety factor of 1.1 and an overall efficiency of the FC system and FP of 50%, the volume of methanol is about 3 m^3.
b) PTI- FULL ELECTRIC MODE: the vessel is sailing at the average speed of 8 kn: the main diesel engine is switched off, eliminating gas and noise emissions. The production of energy necessary for propulsion is reserved for the FCs system and the shaft generator, which, in PTI mode, supplies power to the crankshaft. PTH "Power Take Home" PTH functionality is also available with this mode, which allows the ship, in the event of a main engine failure, to reach the nearest port safely.
Figure 5 shows the scheme of this profile. As result, the ship can operate in hybrid electric mode with both the fuel cell modules operating at 100% load, for a range of about 900 nm.

Figure 5 Navigation at slow Speed Hybrid Electric Mode; Propulsion: 2x500 kWe shaft motors Running; Generators 2x600 kWe FC modules Running at 100%



Considering a safety factor of 1.1, and a complete efficiency FC system and FP of 50%, the volume of methanol is about 55 m^3.
c) PTO - Cruise Mode (CM): in this mode, the vessel is sailing at the cruise speed.
Figure 6 shows the working scheme of this profile.
Propulsion load is predominant, but a consistent hotel load may be present: the main diesel engine takes care of the power required for both propulsion and hotel loads thanks to the presence of the shaft generator.

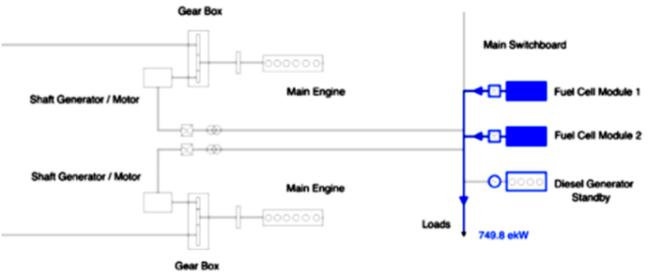
Figure 6 Navigation at service Speed Hybrid Efficient Mode Propulsion 2x 1920 kW Running, 2x shaft generators running and 1x 690 kWe diesel generator in standby



d) Port or Anchor Mode (AM): the ship guarantees zero emission's condition. The loads to be guaranteed is those necessary for the ship's guests to stay in conditions of complete comfort; these powers is provided by two FC modules.

Figure 7 shows the scheme of this profile. The operating profile is as a week (168 h) at anchor or in port, just with FCs running and the diesel generator in stand-by.

Figure 7 Zero emission in port or at anchor; generators: 2x600 kWe FC running; 1x690 kWe diesel generator standby



Considering a safety factor of 1.1, and a complete efficiency of the FC system and FP of 50%, the volume of methanol required for this profile is about 60 m^3. This is the design profile to obtain the volume of methanol to store on board.

METHANOL, FUEL CELL AND REFORMER ARRANGEMENT

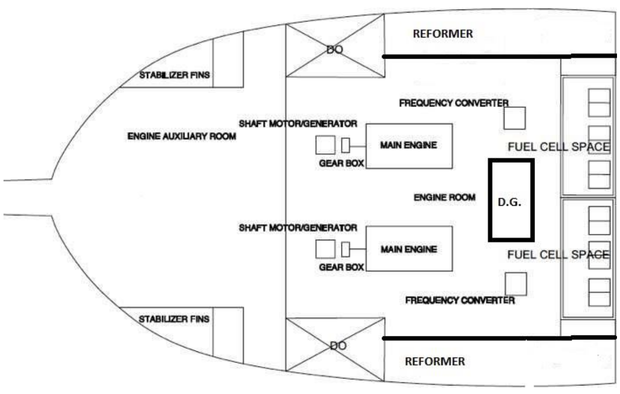
Methanol is highly explosive at standard temperature and pressure, according to the IGF Code, so the tanks are constantly filled with inert gas, such as nitrogen (N_2) or CO_2 that may be produced on board by the methanol clean-up process itself.

To deal with the problem of external damage risk, potentially caused by collision o grounding, according to the IGF Code tanks have to be placed within B/5 with a cofferdam between methanol tanks and shell plating [26]. The resulting volume for the methanol is about 60 m^3 stored in two internal tanks.

The FCs can be stacked in several ways, both next to- and on top of each other, which lead to different required spaces. The choice of the new configuration complies with all the ABS rules for the FCs, allowing two separate air locks that can lead the access both FC space and reformer (see Figure 8).

Having to contemplate the loss of hydrogen from FC stacks, the FC Space is classified as Hazardous Area Zone 1; this provides that the equipment or components installed must minimize the likelihood of gas leakage or a possible explosion.

Figure 8 Propulsion plant space in the Engine Room [11]



IMPACT ON SHIP CHARACTERISTICS

The table 3 shows a comparison between the lightship weights of the reference vessel and the new configuration (limited to the new propulsion and generation systems) [11].

TABLE 3 LIGHTSHIP WEIGHTS REFERENCE VESSEL AND NEW CONFIGURATION [11]

Item	Weight difference
Main Engines	-11.4%
Power System	-36.2%
Reduction Gearboxes	+3.4%
Total	-6.9%

It results that a remarkable reduction in weight can be achieved, that is about -6,9% respect to the reference vessel.

It must be underlined that the hybrid system includes the frequency converters, the electric motors and a margin for auxiliary systems, fluids, foundations, etc., amounting to a total of additional 8.8 t.

The "Power plant" line for the new configuration includes the diesel generator (abt. 6.3 t), the FC modules, reformers and heat exchangers (abt. 6 t) and all relevant auxiliary equipment (cooling lines, exhaust lines etc.)

All the standard loading conditions comply with the intact stability IMO Resolution A.167 criteria, despite them being different from those of the Reference Vessel.

All the tanks containing methanol, fresh water and MGO are not affecting the metacentric height GMt and the stability arm GZ curve, as the free surface effect is negligible; trim and floating are reasonably acceptable in all the loading conditions. The trim may be improved by adding ballast water when necessary.

Concerning the longitudinal strength, an analysis of the bending moment and shear distribution in still water gives [11]:

- the difference, in percentage, between the bending moment of the hull girder in still water is negligible than the old configuration;
- the max bending moment is located at the same frame for both configurations.

CONCLUSIONS

A feasibility study of a Mega-Yacht's hybrid propulsion system with FCs fueled by hydrogen has been presented.

The conventional Diesel propulsion system is analyzed besides one parallel-hybrid system. Different operative profiles have been investigated, including the time spent stationing and the one spent sailing.

The IGF Code on low flashpoint fuels has been considered applicable for the use of methanol on board of a mega yacht; the methanol has been used as hydrogen carrier because rules for carrying hydrogen on board the ship are not developed. The results prove the quantity of methanol obtained to satisfy the required autonomy is compatible to install on board. The installation of a complex system, such as the FCs and the reforming system, electric motors and frequency converters, have not an impact on the speed, trim and stability of the vessel.

Furthermore, the hybrid configuration of the propulsion system has a few impacts on the ship's hull subdivision, displacement, resistance and loads compared to the reference vessel of traditional Mega yacht. In addition is minimal the impacts on reducing crew and guest's capacity.

Fuel Cell Space has been classified as Hazardous Area Zone 1; this provides that the equipment or components installed must minimize the likelihood of gas leakage or a possible explosion. Due to the actual TRL of the Fuel Reformer, it requires attention in terms of dimensions, safety and concentration of CO. Different solutions can be considered for methanol reforming (Steam Reforming, Partial Oxidation, Autothermal Reforming) but Autothermal Reforming seems to be more encouraging to resolve the challenge facing power generation by FCs. This issue is largely debated by scientific and technical community in order to define the best fuel processor system for maritime applications.

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