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THE HYDROGEN-FUELLED INTERNAL COMBUSTION ENGINES FOR MARINE APPLICATIONS WITH A CASE STUDY

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Review paper

Summary

Modern marine power plants have been designed to improve the overall ship's efficiency. This pushed the designers of marine machinery to search for unconventional fuels for these plants. During the previous years, diesel oil has been extensively used on-board ships. Due to the high price of light diesel oil and the environmental problems resulting from the use of heavy fuel oil, it has become necessary to search for an alternative to traditional fuels. As a result, natural gas fuel has been used on-board some types of ships, especially short-voyage cruise ships. Unfortunately, there are still some technical and logistic problems related to the use of natural gas as a fuel, especially as it is considered a non-renewable energy source. The use of hydrogen fuel on-board ships, particularly in modern power plants may contribute to overcoming the above problems. The present paper considers the possibility of the use of hydrogen fuel for marine applications and discusses different stages of hydrogen gas cycle beginning with hydrogen generation process from clean energy until using it as fuel for internal combustion engines on-board one RO/RO ship, named *Taba*, operating in the Mediterranean Sea. Compared to the diesel engine, the hydrogen fuelled engine is found to be lower in thermal efficiency and fuel consumption, however, some adjustments are needed.

Key words: alternative fuels; hydrogen engine; hydrogen storage; ship's emissions

1. Introduction

Marine fuel plays a key role in operation of power plants onboard ships. The latest years have seen difficult challenges against the use of fossil fuels in marine applications due to the environmental damage caused by these fuels. That pushed the International Maritime Organization (IMO) to issue a number of regulations to reduce this effect [1]. Thus, in 2005 the amendments to the Marine Pollution Convention (MARPOL) were issued, i.e. Annex Six of MARPOL, to reduce air pollution from ships. The requirements of Annex Six establish limits on ship emissions. Some of these limits concern the permissible percentage of fuel elements content such as sulphur content [2] while some refer to the percentage of harmful pollutants emitted from ships such as nitrogen oxides [3]. These regulations pressed all interested in the maritime field to consider potential alternatives to reduce dependence on fossil fuels [4-6] and search for alternative types of fuels [7]. Thus, many researchers studied the possibility of using some of alternative fuels, mostly liquefied natural gas [8-10]. Moreover, other researches pointed out the feasibility of using other types of alternative fuels such as methanol [11] and hydrogen (GH_2) [12] for special marine application. On the other hand, it was shown by *Banawan, et.al* [13] that the main obstacles facing the reliance on marine alternative fuels are: availability, cost, reliability, safety and the compliance with IMO regulations. Among alternative fuels, hydrogen is considered to be more environmental friendly and renewable. Despite the safety risks of using hydrogen gas onboard ships, several researches proved the possibility of using it especially for power generation produced by fuel cells [14]. The problem arising now is searching for marine alternative fuels that can be produced through clean energy in order to prevent any further environmental damage caused by production process. The present paper considers the various steps of using hydrogen as an alternative marine fuel, including its production, storage, fuel system, and finally its application in internal combustion engines which represent more than 95% of marine power plants onboard ships. Also, the paper presents a brief introduction to solving the first step of calculations in the problem of Hydrogen Internal Combustion Engines (HICE) designing. A computer model, Engineering Equation Solver (EES) software [15], is used in solving the problem of designing the marine hydrogen engine. Hydrogen gas turbine design can be benefited by using the advantages of the computer programs; which was illustrated in authors' previous work [16-17].

2. Hydrogen production

Hydrogen can be produced from a number of sources both renewable and non-renewable by various processes. At present, a large amount of hydrogen is produced by reforming of hydrocarbons. However, in order to minimize the reliance on conventional fuels, considerable developments in other GH_2 production technologies from renewable resources have been made [18]. The following sections give a short description of hydrogen production methods with emphasis on hydrogen production from clean energy sources.

2.1 Hydrogen from fossil fuels

This method depends on converting the hydrogen-containing materials derived from fossil fuels into a hydrogen-rich gas. Fuel processing of methane is considered to be the most common commercial hydrogen production technology today. By this method hydrogen gas can be produced through three basic technologies: partial oxidation, auto thermal reforming and steam reforming [19]. A major drawback of these technologies is that they produce a huge amount of carbon monoxide (CO). Consequently, additional steps to remove CO are needed. The process of production follows the following equations:

$$CH_4 + H_2O + heat \rightarrow CO + 3H_2 \tag{1}$$

$$CO + H_2O \rightarrow CO_2 + H_2 + heat \tag{2}$$

2.2 Hydrogen from renewable sources

Hydrogen could be also produced by other methods than reforming of fossil fuels, including biomass, pyrolysis, aqueous phase reforming, water electrolysis, photoelectrolysis, and thermochemical water splitting [20].

2.2.1 Hydrogen from solar energy

Solar energy can be used as a source of energy to achieve hydrogen production through water electrolysis, photoelectrolysis, and thermochemical water splitting process [21]. Choice of solar energy for this purpose is the matter of environmental effect [22]. Among the previously mentioned technologies, the solar thermo chemical process is better from the viewpoint of production rate and environmental effect. For example, in traditional thermo-chemical technology, fossil fuels are combusted with air, which emits not only green house gases but also gases that contribute on the ozone layer depletion and acid rains. On the other hand, the solar thermo chemical technology offers either zero or low hazardous gas emissions [23].

As the main purpose of the present research is searching for environmental friendly marine fuel, the emphasis of the paper is on the production of hydrogen using solar energy as renewable source. Figure 1 presents a schematic diagram of solar thermo chemical production of hydrogen using fossil fuels and water (H_2O) as chemical source, including: solar cracking, solar reforming and gasification.

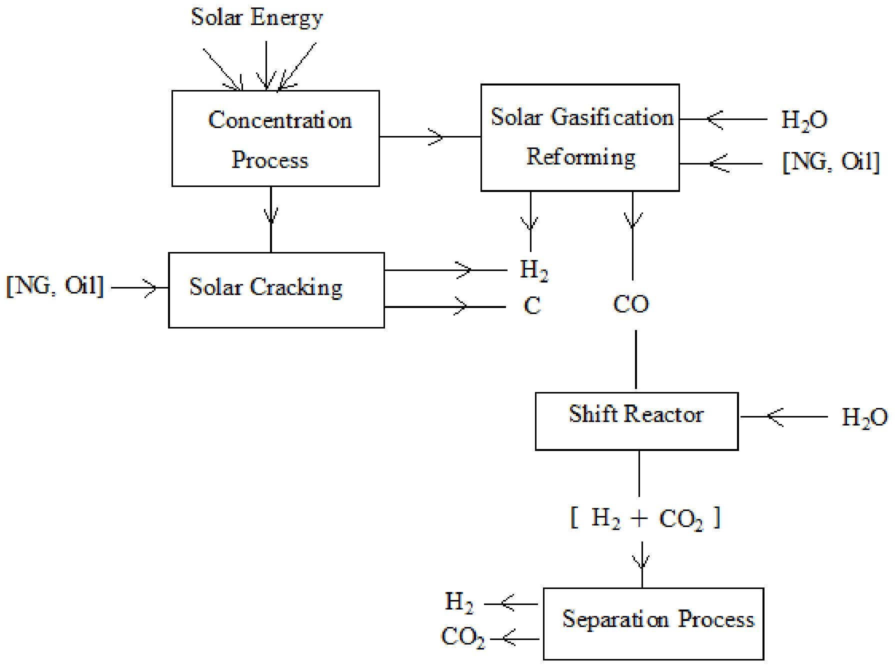

Figure 1 Clean hydrogen fuel production

3. Storage of hydrogen

Hydrogen is an extremely difficult gas to store, this will limit its use until convenient and cost effective storage technologies can be developed and commercialized. One gram of hydrogen gas, for instance, occupies about 12 litres of space at atmospheric pressure. In order to be more convenient, GH_2 must be pressurized under a high atmospheric pressure, and stored in a pressure vessel. In liquid form, hydrogen can only be stored under cryogenic temperatures.

Only the two major problems pending for solutions may make the full application of hydrogen fuel not achievable in the near future: hydrogen storage and production cost. Liquefied hydrogen has a density of 70.1 kg/m^3, which is a very small value if compared to ordinary liquid fuels with densities in the range from 840 to 1010 kg/m^3 [24-25], taking into account that liquid hydrogen heating value is about 3.3 times higher than that for diesel fuel. The production cost cannot be accurately determined since the hydrogen fuel is not produced on a mass production basis. Also, for the two major processes of hydrogen extracting, the water electrolysis and the steam reformation of natural gas; the production process will be more expensive than the ordinary fossil fuels. The cost of removing carbon dioxide (CO_2), resulting from the natural gas steam reformation, increases the cost of the ‘fossil’ hydrogen option. Moreover, cost of hydrogen production by electrolysis is about three times higher than that produced by steam reforming of natural gas.

3.1 Options of hydrogen storage for marine use

Hydrogen storage is considered to be one of the main obstacles against adopting hydrogen as fuel onboard ships due to its very low energy and due to safety issues [26]. In this section, storage alternatives, which include compressed gas, liquefied gas and metal hydrides, are discussed in order to decide which of them will be suitable for marine use. Also, the transportation is discussed with special reference to the liquefied hydrogen (LH_2) carriers under development.

3.1.1 Compressed hydrogen storage

Compressed hydrogen in hydrogen tanks under pressure of 350 bar to 700 bar is used for hydrogen tank systems in vehicles [27]. Storing of hydrogen in form of compressed gas is the simplest storage method. It needs a few devices such as a compressor and a pressure tank. On the other hand, the drawback of this method is low storage density, which depends on the storage pressure.

As the storage pressure increase, capital and operating costs will increase. It is important to know that when compared with traditional fuels, the energy in a compressed hydrogen tank is very low for the same tank volume density. Regarding the economics of this type of storage, both capital and operating costs must be well studied.

3.1.2 Liquefied hydrogen storage

Liquefied hydrogen storage refers to the storage of hydrogen in the liquid state by cooling of hydrogen vapour to the cryogenic temperatures of –253 °C. In addition, it can be stored as a constituent in other liquids, such as $NaBH_4$ solutions, rechargeable organic liquids, or anhydrous ammonia NH_3 [28]. By this method, the weight of hydrogen can be increased by approximately 20 times compared to the compressed form for the same volume [29].

3.1.3 Metal hydride hydrogen storage

Storage of hydrogen in metal hydrides can be achieved through bonding the hydrogen to the surface of metal. Metal hydride hydrogen storage has the following advantages: high hydrogen energy density volumetric capacity, low pressures and low temperatures [30]. The safety of this method is exciting since no leakage is possible if the tank is broken or fractured due to accidents and hydrogen is not released unless heat is provided to break the bonds with the metal. Nevertheless, hydrogen absorption using metal hydrides, chemical hydrides and carbon systems, requires further development and evaluation [31].

There are some factors which play a role when deciding which method of storage might be adopted, including: the required energy density, the amount to be stored, the desired storage period, and the acceptable cost limit. By analyzing the three main systems, the following conclusions can be made: liquid storage − large hydrogen quantities can be stored, long-term storage if permanent cooling is applied, and low electricity costs for liquefaction; compressed storage − small storage quantities, and short storage time; a hydrogen gas tank that contains a store of energy equivalent to a traditional fuel tank would be more than 3,000 times bigger. Of course, this value varies with the pressure, but as already mentioned, higher pressure means higher cost [32].

For marine use, where large quantities of fuel in addition to long storage time are needed, the storage of hydrogen in the liquid state may appear as the best storage form. Although liquid hydrogen can provide a lot of advantages, its uses may be restricted because liquefying hydrogen by existing conventional methods consumes a large amount of heat. Practically, compressed hydrogen storage has short filling time and long storage time, while a liquid hydrogen tank has short filling time and short storage time. Moreover, during the long period of storage, to minimize and control the boil-off losses, the permanent cooling using another medium such as liquid nitrogen is needed, which requires additional costs [33].

4. Hydrogen bunkering process & regulations

The best way of the hydrogen fuel bunkering process will be in the form of liquefied gas. Liquefied hydrogen (LH_2) will be stored in cryogenic tanks at the temperature of 20 K and the amount of bunker fuel will depend mainly on the ship’s sailing time and engines specific fuel consumption. Figure 2 shows the principle components of hydrogen fuel bunkering either onshore or onboard ships. Some other considerations should be taken into account in the fuel amount estimation, such as the expected amount of fuel that has to evaporate to the gas form during consumption of LH_2 to maintain the tank temperature [29].

Bureau Veritas (BV) Classification Society has developed a comprehensive set of guidelines for the use of hydrogen fuel onboard commercial ships. The guidelines combine existing regulations for gas fuelled ships with regulations for terrestrial fuel cell power systems adapted for the application onboard ships. The guidelines are now being tested on a number of pilot projects, of which the Hydrogen-Powered Hybrid Electric Harbour Tug is a good example [34]. Bureau Veritas is looking forward to work together with partners within the industry to further develop the use of clean technologies in shipping [35-36].

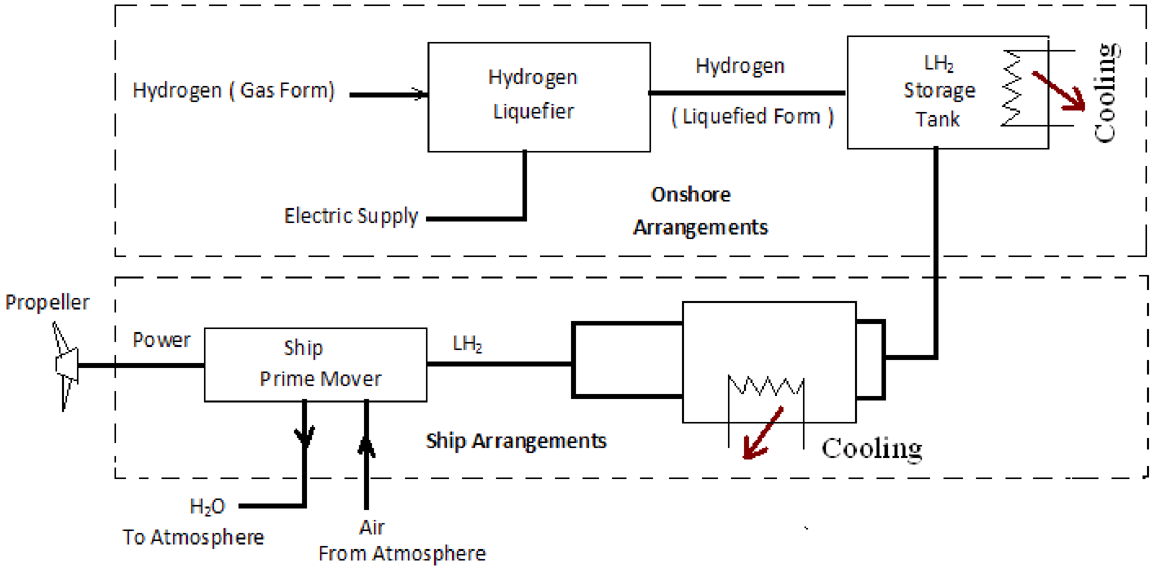

Figure 2 Hydrogen fuel bunkering system

5. Hydrogen-fuelled internal combustion engines

The last decade has produced significant advancements in the development of the hydrogen-fuelled internal combustion engine. The beginning was the use of hydrogen as fuel for spark ignition engines. However, some problems were encountered related to the issues such as pre-ignition, knock, NO*x* control and loss in power density. Therefore, much effort has been put forth in the development of advanced hydrogen engines with improved power densities. The hydrogen fuelled internal combustion engine (H_2ICE) technology passed through several stages as follows [37-38]:

i. Pressure-boosted H_2ICE: problems of pre-ignition, knock and NO*x* control are heightened during boosted operation because boosting pressure increases charge pressure and temperature.

ii. Liquid-H_2ICE was the second phase of H_2ICE development where the primary benefit is the higher stored-energy density of hydrogen available with liquefaction. Moreover, the charge-cooling effect of the cold hydrogen provides for several advantages compared to conventional gaseous port fuel injection. However, practical difficulties of liquid storage include the energy penalty of liquefaction, evaporation during long-term storage, and the cost of onboard cryogenic dewars.

iii. Direct-injection hydrogen-fuelled internal combustion engine (DI-H_2ICE): the direct injection H_2ICE has long been viewed as one of the most attractive advanced H_2ICE options. Preferential of direct-injection hydrogen is based on: the high volumetric efficiency, and the potential to avoid pre-ignition. The challenge with DI-H_2ICE operation is that in-cylinder injection requires hydrogen-air mixing in a very short time.

iv. H_2ICE-electric hybrid: A hybrid-electric version of an H_2ICE offers the potential for improved efficiencies and reduced emissions without the need for aftertreatment. In a hybrid electric system, the ICE operates either in series or parallel with an electric motor.

6. Hydrogen marine power plants

Hydrogen is suggested to be used for the existing diesel engines to minimize the cost as much as possible. The suggested engine will be operated with hydrogen being directly injected into the cylinders, as shown in Figure 3. To initiate the combustion process, low energy sparks will be needed to avoid using amounts of diesel fuel. Fuel pumps and sparks are to be electronically controlled (camless engines) to ensure the optimum performance at various operating conditions, as shown in Figure 4.

One of the main problems related to the adoption of hydrogen for internal combustion engines is the engine knocking that arises due to malfunction of air fuel ratio and intake temperature.

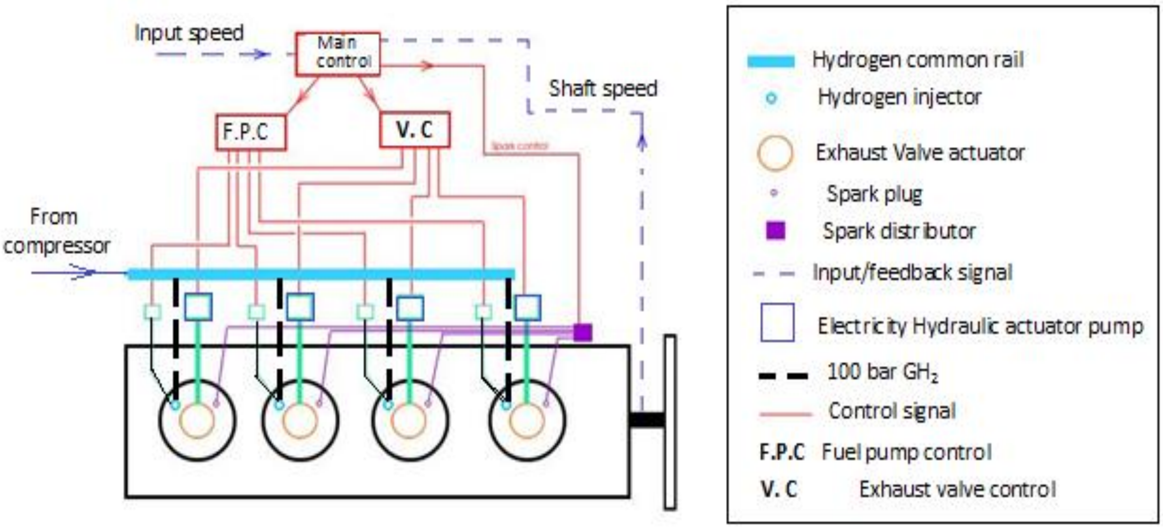

Figure 3 Schematic engine control systems

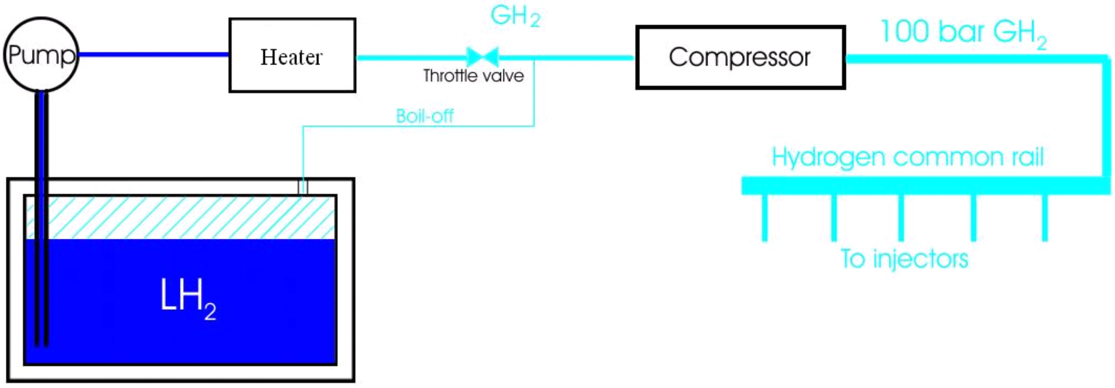

Figure 4 Hydrogen fuel system

Different propulsion arrangements can be used to propel the ship. One of them is to use the hydrogen internal combustion engine connected to the propeller via gearbox, and another one is a modern arrangement – generating electricity by alternators to drive electric motors coupled to the propellers. Each arrangement has its advantages and disadvantages related to the field of usage. Figures 5 and 6 show these arrangements. Smaller hydrogen engines will be needed as shown in Figure 6 for operation at part load in harbours and for manoeuvring purposes, and also for use with auxiliary engines (A/E).

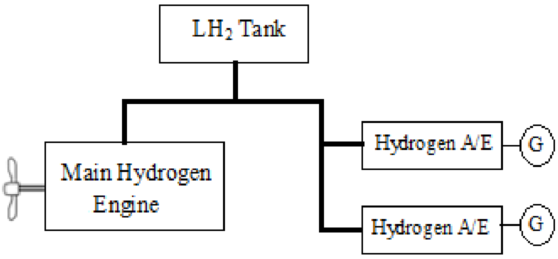

Figure 5 Direct coupling propulsion

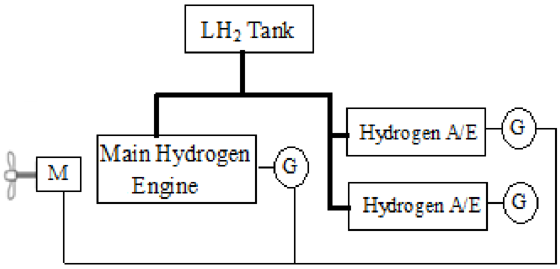

Figure 6 Hydrogen electric propulsion

Generally, waste heat in exhaust gases, which is mainly high temperature, is very important because it eliminates the need for exhaust gas boiler, steam may be directly used onboard ship for heating or for any other process requiring high temperature [39].

Another use of hydrogen is for fuel cells. Huge developments have been achieved in this sector over the past few years. However, in the marine field it has been used only in the naval vessels market for auxiliary power generation and for quiet operation of submarines. Concerning the commercial market, the development achieved so far is not enough to convince ship owners to use this fine technology product. From all types of fuel cells, only two types are the candidates for the use onboard. The proton exchange membrane fuel cell (PEMFC) and the molten carbonate fuel cell (MCFC) fuelled by hydrogen rich fuels like natural gas or alcohols [40].

A number of ship design firms introduced designs for many ship types working with fuel cells as an auxiliary power source or for propulsion in hybrid modes [41]. In the marine sector, several research programs focused on the use of liquid hydrogen onboard ships in combustion engines or fuel cells. Although the use of hydrogen for marine applications provides a lot of advantages, especially regarding environmental issues, it is still restricted due to safety and storage problems.

7. Case study

The case study refers to repowering operation for a RO/RO ship, named *Taba*, operating in the Mediterranean Sea. The ship [42] is originally fitted with 2 MaK 9M453 engines with 2700 kW brake power each. Two alternatives were under consideration, either using pre-mixing of hydrogen and air before entering the combustion chamber or direct injection of hydrogen into the cylinders after compression. The analysis was done for both 2 and 4 stroke cycles based on the Otto standard cycle. The highest useful compression ratio (HUCR) for the hydrogen-air mixture is limited to 6 to avoid explosions [43]. The compression ratio is also limited between 2 and 6; compression ration less than 2 produces a very high combustion temperature and the values higher than 6 produce unstable combustion. Figure 7 shows the comparison between diesel and hydrogen fuels and the variation of combustion temperature at different excess air factor.

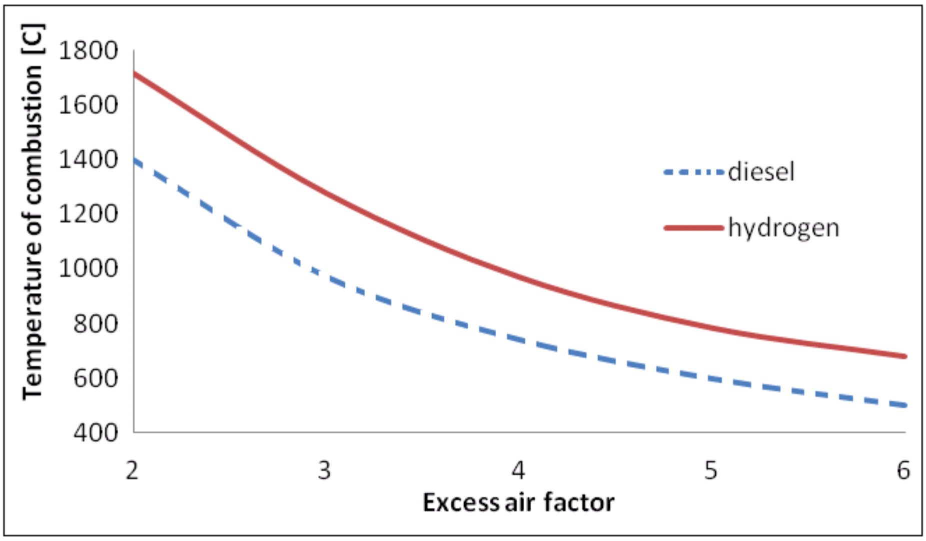

Figure 7 Hydrogen and diesel combustion temperature versus excess air factor

There are some points to be clarified concerning the comparison in Figure 7:

i. The efficiency of the hydrogen engine is lower than that of the diesel engine due to higher cooling water losses in the case of hydrogen. Without all these losses the temperature of combustion inside the cylinders may reach very high levels that may put the engine in a critical state. The obtained result is close to the results published in [44] which demonstrated the ability of achieving efficiency of about 32%.

ii. Due to the higher energy contained in hydrogen, less fuel is used by mass to produce the same power, but the product of fuel consumption and calorific value in both cases will yield a lower value in the case of hydrogen and this is due to lower efficiency.

iii. Very low brake mean effective pressure is available in case of hydrogen if compared with diesel despite the higher turbo charging pressure in the hydrogen engine (in diesel engine only 3.3 bar turbo charging pressure is used), this is due to the different nature of gaseous fuel with a very low density.

iv. Due to lower efficiency and lower density of hydrogen fuel, bigger engine dimensions are needed to produce the same power at the same speed of the diesel engine. It can be concluded that the hydrogen engine is still in need of a considerable effort in order to reach the competition phase. However, attempts to use the hydrogen fuelled engine instead of the diesel fuelled engine must be continued to overcome those obstacles.

Condition (1): Pre-mixing

Temperature = 127^{O}C (at start of compression inside the cylinder) [45]

Pressure = 1 bar (atmospheric),

Compression ratio = 6

Figure 8 shows that at the excess air factor for the bore of 4-stroke exceeds the bore of 2-stroke engines by percentage of 25%. The 2 stroke cycle gives fewer diameters; however, this is larger by 6cm than the installed engine bore of 32 cm. Figure 9 explains the relation between brake specific fuel consumption at different excess air factor.

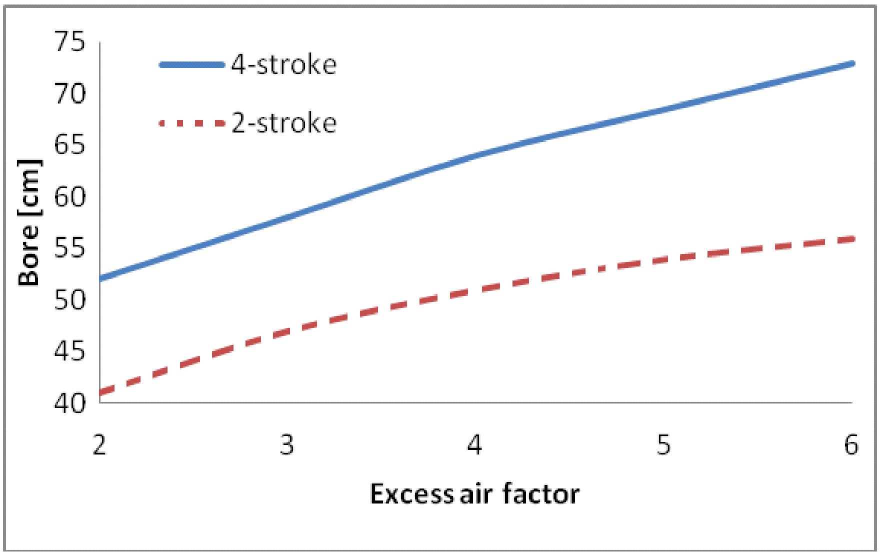

Figure 8 Cylinder bore as calculated for condition (1)

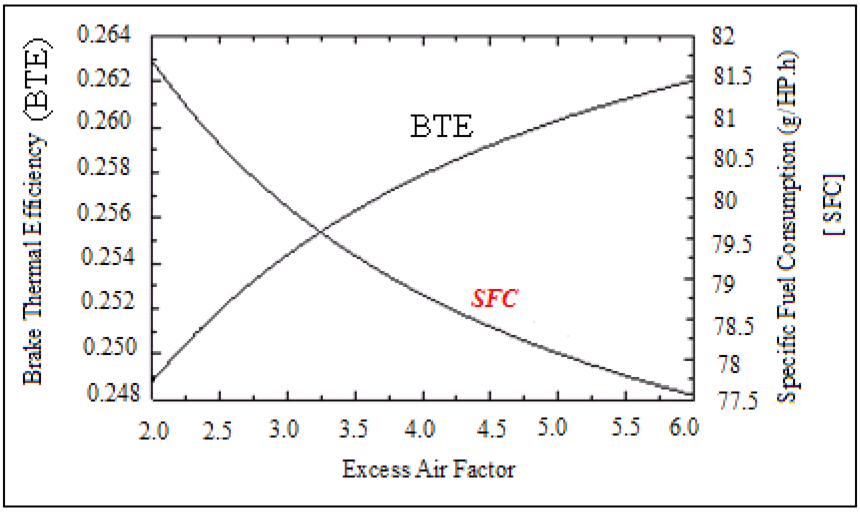

Figure 9 Thermal efficiency and fuel consumption for condition (1)

Condition (2): Direct injection

Temperature = 127^{O}C

Pressure can be varied since no restriction on compression ratio. Figures 10 and 11 illustrate the variation of engine bore at different compression ratio for different pressures for the 4-stroke and 2-stroke engine respectively.

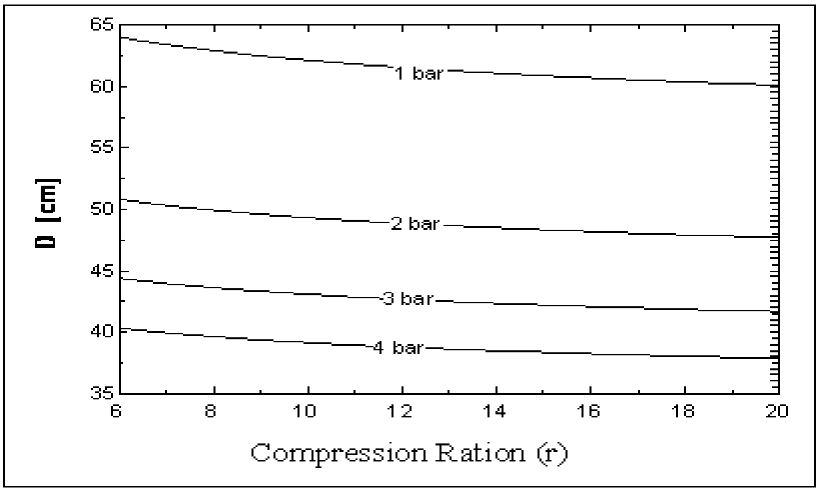

Figure 10 Bore diameter for Condition 2 (4 strokes)

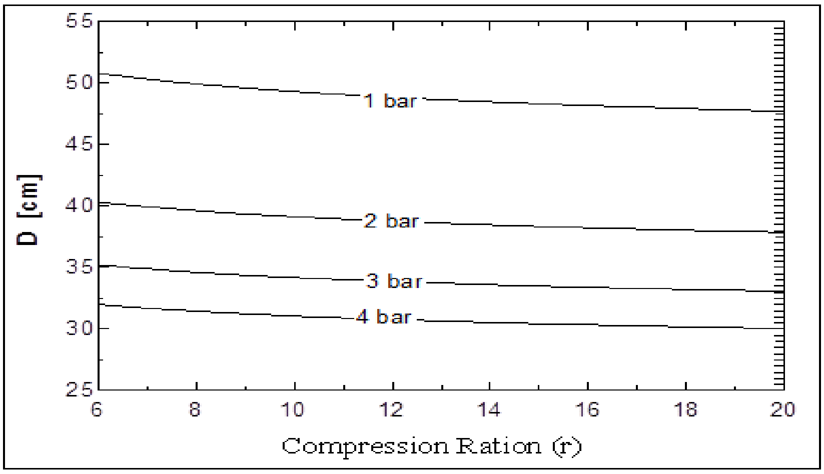

Figure 11 Bore diameter for condition 2 (2 strokes)

The required diameter can be achieved with a reasonable supercharging pressure. Thus, direct injection with 2-stroke cycle is the best choice for the engine design. From Figure 12 is evident that for obtaining the required diameter, a pressure ratio of 9 with supercharging pressure of 3.7 bar is adopted.

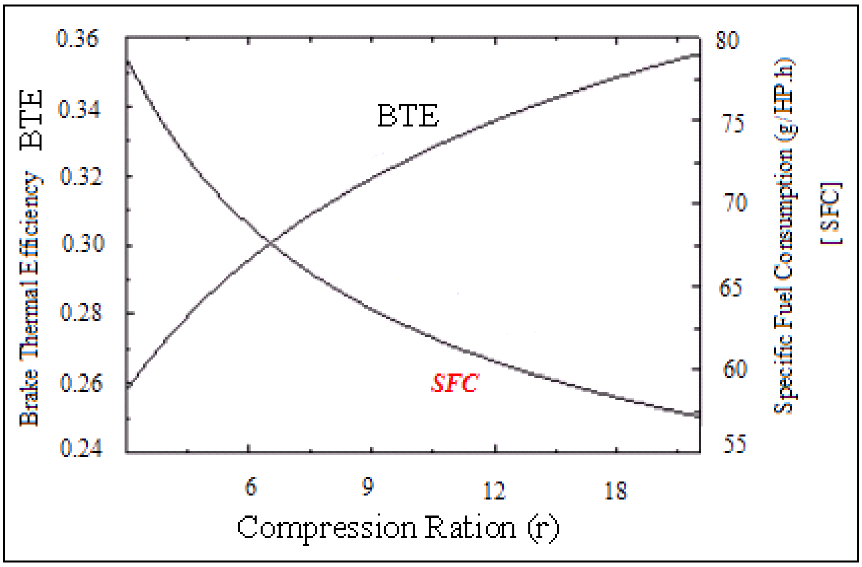

Figure 12 Thermal efficiency and fuel consumption for direct injection condition

The comparison between the engine characteristics of the hydrogen engine and the ship's original engine (M32C Diesel Engine) can be summarized as shown in Table 1.

Table 1 Comparison between engine characteristics of hydrogen engine and M32C diesel engine

	Hydrogen	M32C
Engine speed (r.p.m)	775	600
Pressure ratio	9	12.8
Heating value of fuel (MJ/kg)	130	42.7
Bore (cm)	32	32
Stroke (cm)	42	42
Engine power (kW)	2700	2700
Thermal efficiency (%)	29.57	47
Specific fuel consumption (g/kW.hr)	93.46	178.98
No. of cylinders	6	6
Mean effective pressure (bar)	10.02	25.9
Compression pressure (bar)	75.57	84
Combustion pressure (bar)	132.4	124

The outcome of the preliminary design calculations reveals that the bore of the engine piston will be the same for the two engines, but the thermal efficiency of the hydrogen fuel cycle shows a decline compared to that of the original diesel fuel cycle. On the other hand, the specific fuel consumption is reduced to 93.46 g/kW.hr in case of hydrogen fuel.

The engine flow rates can be summarized as:

Fuel : 93.46 g/kW.hr (252 kg/hr)
Cooling water : 67.83 kg/kW.hr (183007 kg/hr)
Air : 13 kg/kW.hr (35087 kg/hr)
Exhaust : 13.1 kg/kW.hr (35339 kg/hr)

Regarding the fuel storage tanks onboard the ship; the volume of the ship fuel tanks (DMA and DMB) is 706.8 m^3. When these tanks are used for LH_2, only 90% of this volume can be filled due to insulations. Thus, volume will be 636.1 m^3. The volume of LH_2 required for 8 days' voyage (2~3 stops in ports) is 1492 m^3. This means that the present volume, for complete hydrogen power plant, i.e. both the main engines and the generators run on hydrogen, will be sufficient only for a voyage of 3.4 days. Consequently, the extra volume of about 950 m^3 will be needed. This volume can be deducted from the twine deck area as shown in Figure 13. As can be seen, two times larger tank space in the ship under consideration is needed to accommodate the hydrogen fuel for only 8 days rather than 20 days as the ship originally travels.

This problem will occur only in cases when considering the conversion of existing ships to run on hydrogen, but new designs should include their own hydrogen tank spaces. Another solution may be available if new storage techniques are invented to overcome this problem. New techniques are required to provide fuel storage with appropriate energy density.

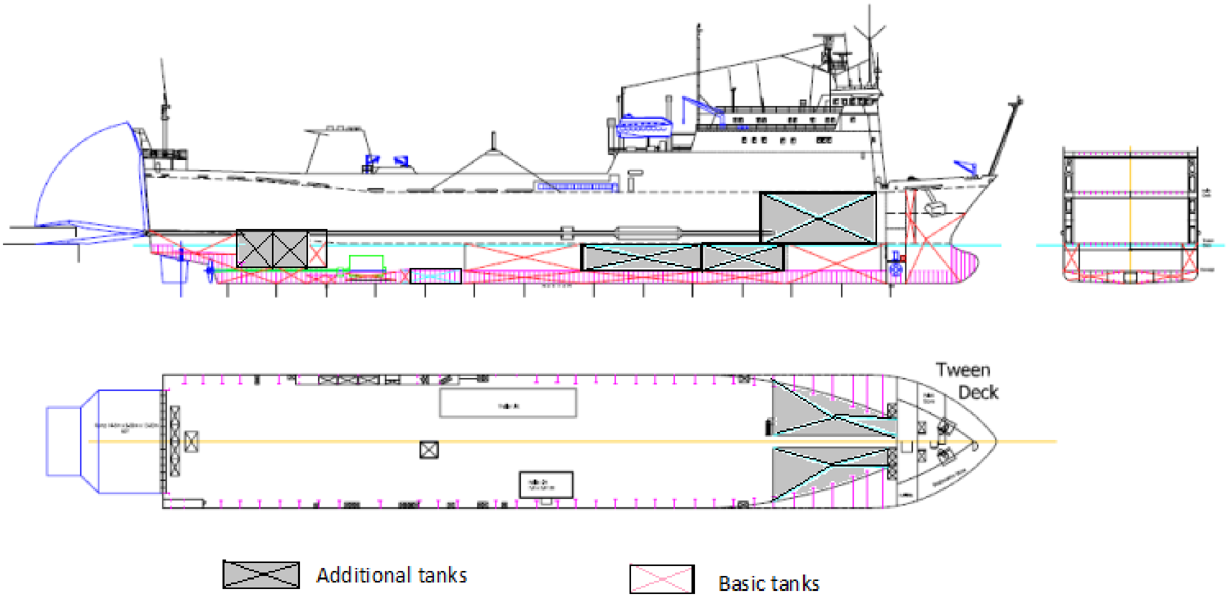

Figure 13 Modified hydrogen fuel tanks

8. Conclusion

Several issues must be taken into consideration when trying to adopt a new type of fuel like hydrogen, especially for marine applications where strict rules and regulations control the design and manufacture of waterborne vehicles. Safety and storage problems are the main issues arising when talking about the use of hydrogen as fuel. Combustion of hydrogen inside internal combustion engines has been, and still is, the subject of numerous research programmes in many countries. Like in the case of natural gas, one of the main problems associated with the application of hydrogen in internal combustion engines is engine knocking; air fuel ratio and intake temperature were found to be the main causes for this problem and their optimization is a must in order to have a knock free engine.

The present paper discussed the different stages of hydrogen gas cycle beginning with the production process, from clean energy, until using it as fuel for internal combustion engines onboard a RO/RO ships, named *Taba*, operating in the Mediterranean Sea. Compared to the diesel engine, the hydrogen engine was found to be lower in thermal efficiency, mean effective pressure and fuel consumption, while the both engines seemed to have the same value of compression and combustion pressure. In addition, some adjustments are needed regarding the engine’s dimensions, valves timing and fuel system.

However, regarding the ship’s operation, some problems need to be solved. First of all, it is necessary to make some modifications for the use of hydrogen onboard ships, like for instance, the fuel storage capacity, as the fuel tanks of the ship under research are not capable to accommodate the hydrogen needed. The study has shown the need to increase the volume of bunkering tanks from 706.8 m^3 (heavy and diesel fuel) to 1492 m^3 (hydrogen fuel) so that the vessel can provide the necessary space for the hydrogen storage. The design results may seem strange to the professional reader and yield to the heavy, big and expensive engine, but it must not be forgotten that this is a first step. Other refinement procedures will follow and also prototype experiments have to be made to assess how far the calculations are from the real world and after that a fine tuning processes will follow. This procedure can also be applied to different types of power plants.

Acknowledgment

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Nomenclature

A/E	Auxiliary engines	HUCR	Higher Useful Compression
B.V	Bureau VERITAS	IMO	International Maritime
BTE	Brake Thermal Efficiency	LH_2	Liquefied hydrogen
CO	Carbon Monoxide	MARPOL	Marine Pollution
EES	Engineering Equation Solver	NOx	Nitrogen-Oxides
GH_2	Gas Hydrogen	P.M	Particulates Mater
HC	Hydrocarbons	SOx	Sulfur- Oxides
HICE	Hydrogen Internal		

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