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Overview of the Green Hydrogen Applications in Marine Power Plants Onboard Ships

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Abstract

The need for renewable and green energy sources to replace fossil fuel with the incrementally rising prices is driving many researchers to work on narrowing the gap between the most scientific innovative clean energy technologies and the concepts of feasibility and cost-effective solutions. The current paper aims to introduce one aspect of Green Energy; the use of Hydrogen as fuel for marine power plants, to replace all kinds of fossil fuels which are the major responsible of harmful emissions. There are three applications for hydrogen in marine field. These applications include hydrogen internal combustion engines, hydrogen gas turbines, and fuel cells. The main problems associated with the application of hydrogen in internal combustion engines are the engine knocking; air fuel ratio and intake temperature. The research programs for the application of hydrogen in gas turbines concentrate on studying the characteristics of hydrogen combustion inside gas turbine combustors. The third application of hydrogen is fuel cells. Huge developments have been achieved in this sector over the past few years. But for the marine field only the naval vessels market used it for auxiliary power generation.

Keywords: *Green Hydrogen, ICE, Gas turbine, Fuel cell, Marine power plant.*

1. Introduction

The world is facing a challenge in meeting its needs for energy. Global energy consumption in the last half-century has increased very rapidly and is expected to continue to grow over the next 50 years. However, it is expected to see significant differences between the last 50 years and the next. This is leading to accelerated efforts to find new ways to derive and produce energy. Over the coming 20 years the world economy will be adjusting itself to accommodate a wide range of systems to produce the needed energy. These systems will rely less on current fossil fuels and more on a wide range of new sources, including renewable forms of energy such as solar, wind and biomass sources as well as nuclear sources. In addition to that, hydrogen produced from the renewable energy considered a good solution [1].

Hydrogen, while the most basic and ubiquitous element, faces important challenges to cost effective and environmentally sound production, storage and distribution at the scale that markets will require. In these scenarios, hydrogen is likely to play a vital role as the energy carrier of choice to bring the energy from sources of production to points of consumption. Hydrogen applications in marine field include hydrogen internal combustion engines, hydrogen gas turbine, and fuel cells [2].

2. Hydrogen as a fuel in marine field and hydrogen infrastructure

Hydrogen atom is the lightest element, with its most common isotope consisting of only one proton and one electron. Hydrogen atoms readily form H_2 molecules, which are smaller when compared to most other molecules. The molecular form, simply referred to as hydrogen is colorless, odorless, and tasteless and is about 14 times lighter than air, and diffuses faster than any other gas. On cooling, hydrogen condenses to liquid at −253°C and to solid at −259°C. Ordinary hydrogen has a density of 0.09 kg/m^3 [3].

Hydrogen is found everywhere on Earth in water, biomass, natural gas, and all living things yet it is rarely found in its free elemental form. Hydrogen must be liberated from the chemical compounds in which it is found using some form of energy. Natural gas (methane) has four atoms of hydrogen per carbon atom and is the

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limit of decarbonization without going all the way to hydrogen, which is obviously a carbon-free fuel; as shown in Figure (1) [4].

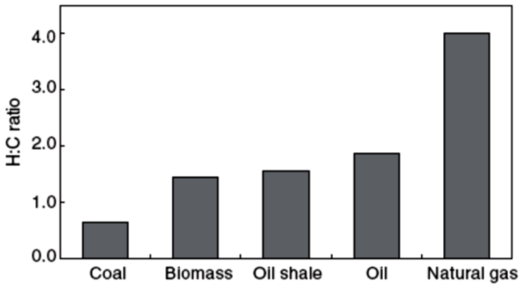

Figure 1 Hydrogen to carbon atomic ratios in carbon-based fuels. 'Oil' refers to heavy residues and other petroleum fractions

Hydrogen infrastructure is required for hydrogen production, storage, and distribution and, in the case of transport; special facilities will be required for vehicle refueling. This has implications for land use planning as well as for the safe operation and maintenance of hydrogen equipment. Other issues must also be addressed. There is already substantial production of hydrogen in the world (about 50 million tons annually), for use in fertilizer (ammonia), methanol manufacture and other industrial activities. The worldwide consumption of hydrogen was below 200 billion cubic feet in 1991, and reached 1,800 billion cubic feet in 2010 [5].

Hydrogen can be produced in many different ways, using a wide range of technologies. Some of these involve established industrial processes while others are still at the laboratory stage. Some can be introduced immediately to help develop a hydrogen energy supply system; while others need considerable research and development.

Hydrogen storage is a common practice in industry, where it works safely and provides the service required. Also, hydrogen can easily be stored at large scale in vessels or in underground caverns. Conventional storage, such as compressed gas cylinders and liquid tanks, can be made stronger, lighter and cheaper.

The following equations represent the change in density (ρ) of hydrogen gas at various temperatures and pressures. These equations are based on the ideal gas law with a compressibility factor (Z) for the hydrogen gas the gas pressure and temperature respectively and R is the gas constant for hydrogen (4157 N m / kg K).

$$\rho = P / ZRT \quad (1)$$

$$Z = 0.99704 + 6.4149E\text{-}9\ P \quad (2)$$

Where, P (Pa) is the pressure of the gas, VH (m^3) is the volume and T (K) is its temperature. Using the gas constant given above, the equation can be restated as follows.

$$V_H = \frac{4157.2 \times Z m_H T}{P} \quad (3)$$

The tank radius (r) can be calculated from the volume determined in the previous equation. The tank is assumed to be either a sphere or a cylinder. The sphere is actually a special case of the cylinder in which the length (L) is zero. Next equation can be solved for r through an iterative process.

$$V_H = \frac{4\pi r^3}{3} + \pi r^2 L \quad (4)$$

The energy density of gaseous hydrogen can be improved by storing hydrogen at higher pressures. This requires material and design improvements in order to ensure tank integrity. Hydrogen storage depends on the storage pressure and temperature as shown in Figures (2, 3).

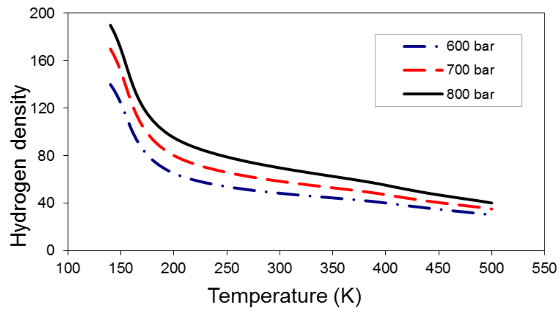

Figure 2 Relation between hydrogen density and temperature at different pressures

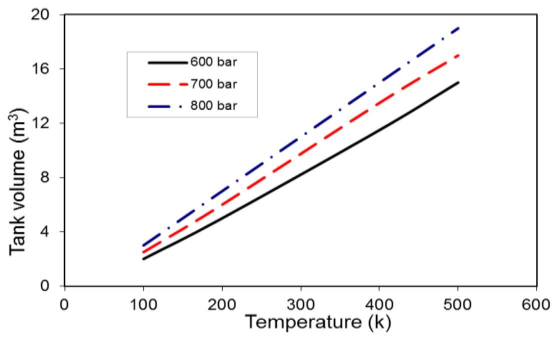

Figure 3 Relation between tank volume and temperature at different pressures

Regarding the hydrogen safety which is a very important issue to be considered especially when talking about the marine field where strict safety rules and regulations have to be met, Table 1 shows some characteristics related to fuel safety; the flammability limits of hydrogen in air seem to introduce high risk of explosion in case of hydrogen leakage but in a well-ventilated space this risk is highly reduced due to the high diffusion rate of hydrogen if compared to natural gas for example.

Table1 Comparison between the three types of fuels[6, 7]

Fuel property	Diesel	Natural gas	Hydrogen
Density [Kg/m^3]	850-1000	0.65 gas 422.8 liquid	0.08 gas 70.1 liquid
Calorific value [MJ/kg]	40-43	50	120
Flammability limits [%]	0.6-5.5	5.3-15	4-75
Self ignition temp. [°C]	340-350	540	585
Diffusion coefficient [cm^2/sec]	0.05	0.16	0.61
Min. ignition energy [mJ]	0.24	0.29	0.02

3. Hydrogen fuel in internal combustion engines

Combustion of hydrogen inside internal combustion engines has been, and still is, the subject for many research programs in many countries. Like the natural gas one the main problems associated with the application of hydrogen in internal combustion engines include the engine knocking; air fuel ratio and intake temperature were find to be the main causes for this problem and their optimization is a must to have a knock free engine.

Some problems were discovered to be only related to the hydrogen due to its special characteristics; these characteristics are the high flame speed and the low ignition energy, the problems associated are the steep rise of cylinder pressure and possibility of fuel pre-ignition leading to potential explosions inside the engine systems [7].

Regarding the emissions, it is evident that the hydrogen produces fewer emissions almost in all engine operating conditions, due to the higher combustion temperature in hydrogen engines, the NO_x rates were found high in some cases and many solutions were produced, all of them use well proved technologies used nowadays with normal engines, these technologies include exhaust gas recirculation and catalytic reduction filters.

Most of the researches done on hydrogen internal combustion engines have as result a slight increase in the engine thermal efficiency with a decrease in engine output power and torque [8].

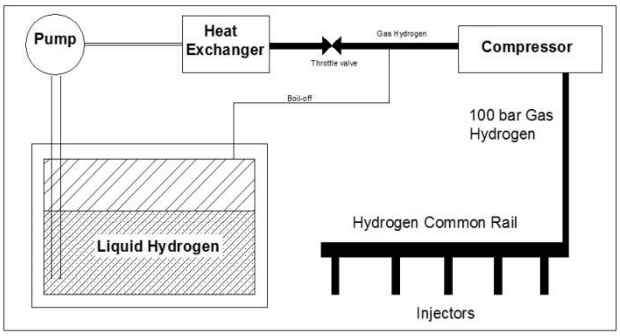

Figure 4 Hydrogen fuel systems

Hydrogen is to be used as a marine fuel in internal combustion engines; to make use of the existing diesel engines used in order to prevent manufacturing new systems and minimize the cost to only modifications to existing engines. The suggested engine will operate on hydrogen directly injected into the cylinders as shown in Figure (4). Low energy sparks will be needed to avoid using amounts of diesel fuel in order to initiate combustion. Fuel pumps and sparks are to be electronically controlled (cam less) to ensure the optimum performance at various operating conditions.

Many propulsion arrangements exist to propel the ship, one of them is to use the hydrogen internal combustion engine connected to the propeller via gearbox as in Figure (5), and another one is a modern arrangement, by generating electricity by alternators to drive electric motors coupled to the propellers as can be shown in Figure (6). Each arrangement has its advantages and disadvantages according to the field of usage. The next figure shows these arrangements.

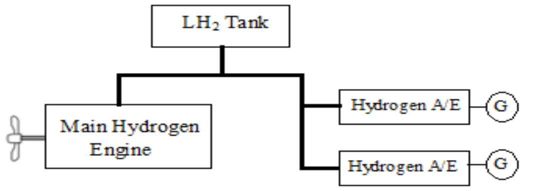

Figure 5 Direct coupling propulsion

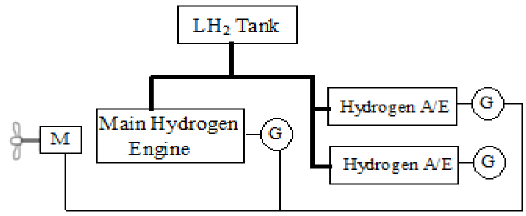

Figure 6 Hydrogen electric propulsion

Smaller hydrogen engines will be needed as shown in previous figure for operation at part load in harbors and for maneuvering purposes and also for use with electric generators.

Waste heat in exhaust which is mainly high temperature steam is very important because it eliminates the need for exhaust gas boiler, steam in the exhaust may be directly used onboard ship for heating or any other process requiring high temperature [9, 10].

4. Hydrogen marine gas turbine

Since 130 BC, when Hero of Alexandria attempted the first reaction steam turbine and the experiments didn't stop to invent a fully working steam or gas turbine. Until 1900, none of the trials were successful to produce a gas turbine, until Dr. Franz Stolze succeeded in producing a prototype; it has the main components as today's gas turbine, based on his researches dated back to 1872. But this unit never ran successfully [11].

Regarding the marine use of gas turbines it didn't start until the 1970's, the major client for marine gas turbines is the naval units where lots of naval forces worldwide use them as main or auxiliary power generators for their ships. Recently, the marine gas turbine started slowly to penetrate the commercial market as auxiliary power units especially in large cruise liners as Queen Mary II, and it is anticipated to penetrate more and more in other commercial sectors as many favorable issues are convincing the ship owners to use gas turbines rather than diesel engines in new built ships. Table 2 shows the main characteristics of modern gas turbines.

Table 2 Main characteristics of conventional marine gas turbine [10]

Specific data	Gas turbines	
Process	Simple cycle	Advanced cycle
Construction	2-shaft	2-shaft
Output [kW]	6000-26000	24000
Speed [rpm]	3600-7000	3600
Fuel	MDF	MDF
SFC [g/kWh]	240-280	200
Spec. NOx emissions [g/kWh]	2-5	3
Specific mass [kg/kW]	1.0-1.4	1.8
Specific cost [Euro/kW]	180-280	470

The gas turbine engine is designed based on the Brayton cycle, which is an ideal cycle working with a perfect gas. In the preliminary stages of design the working fluid is assumed to be only air, but in the next stages this assumption is modified to include the fuel type used by modeling the main properties of the mixture.

Figure (7) shows the temperature–entropy and pressure – volume diagrams for the Brayton cycle. Compression takes place in the compressor (1-2), this compressor may be of the axial or centrifugal type according to the engine rating, where axial compressors are most suitable for high power gas turbines . Next to the compression, combustion or heat addition takes place (2-3) where temperatures in the order of 1200 K to 1500 K may be reached [12].

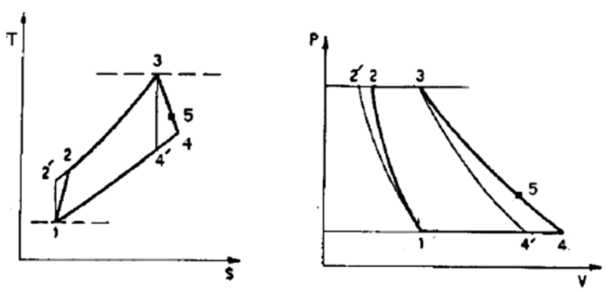

Figure 7 T-S and P-V diagram for ideal gas turbine cycle with free power turbine

After the combustion, the high pressure hot gases enter the turbine to extract their energy by expansion (3-4), this process takes place on two stages; the first in the compressor turbine (3-5) where only enough power to run the compressor is generated, the second stage in the power turbine (5-4) where the remaining energy in the hot gases is extracted to generate useful work. This configuration as in Figure (8) is called split or twin shaft gas turbine since each turbine run on separate shaft with different speeds [13].

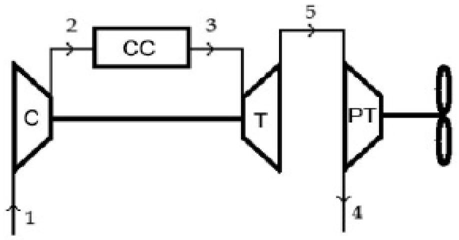

Figure 8 Schematic diagram of the split shaft marine gas turbine

Where C = compressor
CC = combustion chamber
T = Turbine
PT = Power turbine

For the application of hydrogen in gas turbines, the scientific community witnessed many research programs and technical investigations to study the characteristics of hydrogen combustion inside gas turbine combustors. Basically there are three methods applied in the gas turbine market to reduce emissions from ordinary gas turbines powered by petroleum products or natural gas; dry low NO_x combustors, flame dilution by the addition of steam or adding catalytic reducers at the exhaust systems. Not all of these techniques can be used with hydrogen due to its special combustion characteristics.

All researches have common conclusions; NO_x emission levels for the direct substitution of natural gas or other fuel oils result in an increase in NO_x levels and the reduction of these levels necessitates additional modification to be made on the combustor design in the dry combustor designs or increase the rate of dilution achieved by steam addition.

In order to achieve the maximum benefits from using the hydrogen, many ideas encouraged the use of blends of natural gas with hydrogen with different proportions either in internal combustion engines or gas turbines, the results for engines showed the modification of the natural gas case when the emissions are considered, but for the gas turbine, the admission of hydrogen to natural gas in ordinary combustors without special measures to reduce NO_x resulted in an increased emission rate [14].

5. Hydrogen Marine Fuel cell power plant

Research into fuel cells began with hydrogen and oxygen as reactants in 1838, expanded during attempts to use coal as fuel, and flourished after 1950 when the technology found its first prominent application in space missions. In 1845 (50 years before the advent of the internal combustion engine) the first fuel cells, studied by the German chemist Christian Friedrich Schönbein and the Welsh scientist Sir William Robert Grove and called "gaseous voltaic batteries," demonstrated the electrochemical reaction of hydrogen and oxygen in a time when the chemical combination of the reactant gases was known to occur on platinum [15].

Fuel cells are electrochemical devices that convert chemical energy in fuels into electrical energy directly, promising power generation with high efficiency and low environmental impact. Because the intermediate steps of producing heat and mechanical work typical of most conventional power generation methods are avoided, fuel cells are not limited by thermodynamic limitations of heat engines such as the Carnot efficiency. In addition, because combustion is avoided, fuel cells produce power with minimal pollutant [16].

For most practical fuel cell applications, unit cells must be combined in a modular fashion into a cell stack to achieve the voltage and power output level required for the application. Generally, the stacking involves connecting multiple unit cells in series (the Bipolar Plate) via electrically conductive interconnects. Different stacking arrangements can be shown in Figure (9).

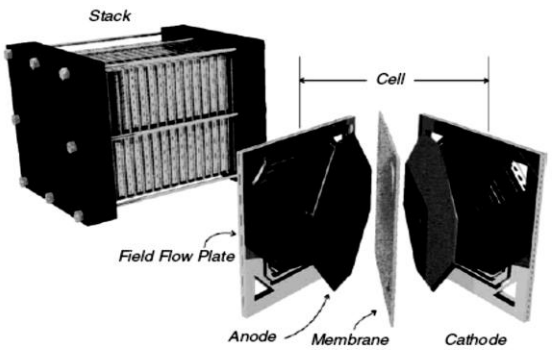

Figure 9 Fuel cell stack made up of flow field plates (or bipolar plates)

Fuel cells can be classified by use of diverse categories, depending on the combination of type of fuel and oxidant, whether the fuel is processed outside (external reforming) or inside (internal reforming) the fuel cell, the type of electrolyte, the temperature of operation, whether the reactants are fed to the cell by internal or external manifolds, etc. The most common classification of fuel cells is by the type of electrolyte used in the cells and includes:

1) Polymer electrolyte fuel cell (PEFC).
2) Alkaline fuel cell (AFC).
3) Phosphoric acid fuel cell (PAFC).
4) Molten carbonate fuel cell (MCFC).
5) Solid oxide fuel cell (SOFC).

Fuel cells have many favorable characteristics for energy conversion. As explained earlier, they are environmentally acceptable due to a reduced value of carbon dioxide (CO_2) emission for a given power output. Moreover, the usage of fuel cells reduces transmission losses, resulting in higher efficiency. Typical values of efficiency range between 40%-85%. Another advantage of fuel cells is their modularity. They are inherently modular, which means that they can be configured to operate with a wide range of outputs, from 0.025-50 MW for natural gas fuel cells to 100 MW or more for coal gas fuel cells [9, 17]. Fuel cells have the ability to maintain efficiency through a range of loads, at loads between 30 to 100 percent of rated output. Conventional systems, on the other hand, are less efficient at the lower end of this range as shown in the following Figure (10).

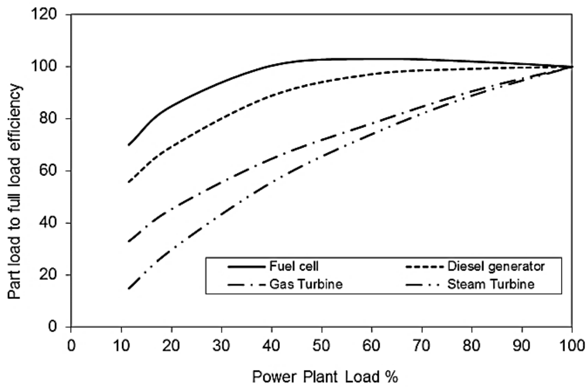

Figure 10 Ship Service Fuel Cell (SSFC) efficiency compared to different power plants [18]

The above types can be broadly classified in terms of their temperature of operation into:

1) Low-temperature (50–150^{o}C): alkaline electrolyte (AFC), and proton-exchange membrane (PEMFC) ;
2) Medium-temperature (around 200 ^{o}C): phosphoric acid (PAFC) fuel cell;
3) High-temperature (600-1000 ^{o}C): molten carbonate (MCFC), direct carbon (DCFC) and solid oxide (SOFC) fuel cells.

Conclusions

Using hydrogen as fuel is a well proven application for the most abundant substance in the universe. Many car manufacturers introduced car models working with liquid or gaseous hydrogen along with internal combustion engines or fuel cells. For the marine sector, several research programs focused on using liquid hydrogen onboard ships in combustion engines or fuel cells. Also, many ship design firms introduced designs for many ship types working with fuel cells as auxiliary power source or for propulsion in hybrid modes. The current hydrogen production methods do not allow it to be totally clean fuel as these methods use fossil fuels and emit large quantities of carbon dioxide into the atmosphere; only 4% of the global hydrogen production uses renewable sources such as solar energy.

Several issues must be taken into consideration when trying to adopt a new type of fuel like hydrogen, especially when this fuel is intended to be used in the marine field where strict rules and regulations control the design and manufacture of waterborne vehicles. Safety and storage problems are the main problems arising when talking about the use of hydrogen as fuel.

Hydrogen can be used as a marine fuel in internal combustion engines; to make use of the existing diesel engines used and only modifications can be done to existing engines. The challenge of hydrogen gas turbine is in the adoption of the new type of fuel for waterborne vehicles and also the difference between the properties of hydrogen and those of other types of fuels. Fuel cells, one of the emerging technologies in distributed generation, have been hindered by high initial costs. However, costs are expected to decline as manufacturing capacity and capability increase and designs and integration improve.

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