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THE USE OF HYDROGEN ON BOARD SHIPS

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ABSTRACT

Hydrogen, the carbon-free energy of tomorrow, is being explored as a potential fuel for ship propulsion. It is considered a clean and sustainable alternative to traditional fossil fuels, as it produces zero emissions when used in fuel cells or burned in engines. Hydrogen-powered ships have the potential to significantly reduce greenhouse gas emissions and contribute to decarbonizing the maritime industry. However, it is important to note that the adoption of hydrogen as a mainstream fuel for ships is still in the early stages, and there are various technical and infrastructure challenges that need to be addressed for its widespread implementation.

Keywords: hydrogen, fuel cells, risks, renewable energy, development

1. INTRODUCTION

The adoption of hydrogen as a mainstream fuel for ships faces several technical challenges that need to be addressed. Some of these challenges include:

1. Storage and handling: Hydrogen has a low energy density, which means it requires larger storage volumes compared to traditional fuels. Finding efficient and safe ways to store and handle hydrogen onboard ships is a significant technical challenge.

2. Infrastructure: Establishing a hydrogen infrastructure, including production, storage, and distribution facilities, is crucial for the widespread adoption of hydrogen as a ship fuel. Developing a robust infrastructure that can support the supply and availability of hydrogen is a complex task.

3. Safety considerations: Hydrogen is highly flammable and requires careful handling to ensure safety. Developing appropriate safety protocols and technologies to prevent accidents and mitigate risks associated with hydrogen fuel is essential.

4. Conversion technologies: Ships currently rely on internal combustion engines or other propulsion systems that are designed for conventional fuels. Adapting or developing new propulsion technologies that are compatible with hydrogen fuel is a technical challenge that needs to be overcome.

5. Cost and efficiency: Hydrogen production, storage, and distribution can be expensive, and the overall efficiency of hydrogen-based propulsion systems needs to be optimized. Finding cost-effective solutions and improving the efficiency of hydrogen technologies are important considerations for its mainstream adoption.

Addressing these technical challenges will require significant research, development, and collaboration among industry stakeholders, governments, and research institutions to make hydrogen a viable and sustainable fuel option for ships.

2. HYDROGEN COMPATIBLE PROPULSION TECHNOLOGIES

There are several propulsion technologies that are being explored or developed to be compatible with hydrogen fuel for ships. Some of these include:

1. Fuel Cells: Hydrogen fuel cells convert hydrogen and oxygen into electricity, which can power electric motors for propulsion. Fuel cell systems offer high efficiency and zero emissions, making them a promising option for hydrogen-powered ships.

2. Internal Combustion Engines (ICE): Adapting internal combustion engines to run on hydrogen is another approach. Hydrogen can be burned in an ICE, similar to traditional fossil fuels, but without producing greenhouse gas emissions. However, modifications are required to optimize combustion and address potential issues such as pre-ignition and backfire.

3. Gas Turbines: Gas turbines can also be modified to burn hydrogen as a fuel. Hydrogen combustion in gas turbines can provide high power output and efficiency. However, challenges such as flame stability and controlling emissions need to be addressed.

4. Hybrid Systems: Hybrid propulsion systems that combine hydrogen fuel cells or hydrogen combustion engines with energy storage technologies, such as batteries or supercapacitors, are being explored. These systems can optimize efficiency and provide power for peak demands.

It's important to note that the development and implementation of these technologies are still ongoing, and each has its own advantages and challenges. Further research, testing, and collaboration among industry stakeholders are necessary to refine and optimize these propulsion technologies for hydrogen-powered ships.

Hybrid propulsion systems that combine hydrogen fuel cells or hydrogen combustion engines with energy storage technologies, such as batteries or supercapacitors, work by utilizing the strengths of each technology to optimize efficiency and performance.

In a hybrid system, hydrogen fuel cells or combustion engines generate electricity by converting the chemical energy of hydrogen into electrical energy. This electricity can be used to power the ship's propulsion system directly or charge the energy storage devices, such as batteries or supercapacitors.

The energy storage devices in the hybrid system serve multiple purposes. They can store excess energy generated by the fuel cells or engines during low power demand periods and release it during high power demand periods, providing power on-demand and optimizing the overall efficiency of the system. Additionally, they can provide additional power during peak demand periods, reducing the strain on the fuel cells or engines and improving their longevity.

The integration of energy storage technologies in hybrid propulsion systems also allows for regenerative braking or energy recapture. When the ship decelerates or stops, the energy generated from the braking process can be captured and stored in the energy storage devices for later use, further improving efficiency and reducing energy waste.

Overall, hybrid propulsion systems combining hydrogen fuel cells or combustion engines with energy storage technologies offer the advantages of clean and efficient hydrogen power while optimizing energy usage, improving performance, and reducing emissions in maritime transportation.

3. HYDROGEN – SOME DATA

The Hydrogen, rare in monatomic form (H), can be isolated in the molecular state (H_2). It is the lightest gas: at equal volume, 14 times lighter than air (at atmospheric pressure). It is colorless and odorless, insoluble in water.

The combustion of hydrogen with oxygen produces water: $H_2 + ½ O_2 \rightarrow H_2O$ + heat.

A lot of energy is released during the oxidation of hydrogen::

- H_2: 33.3 kWh/kg
- Diesel: 12 kWh/kg

However, hydrogen is characterized by a low density:

- 1 kg of hydrogen gas = ~11 m^3 at atmospheric pressure and room temperature
- 1 kg of gasoline = ~1.2.10^{-3} m^3

Hydrogen is stored in tanks in gaseous format or cryogenic tanks in liquid state (-253°C). The solution in gaseous form is currently the most available to date for the maritime sector. However, the volumes to be integrated for storage in gaseous format (under pressure) remain significant:

1 kg of hydrogen gas at 350b = ~40.10-3 m^3
1 kg of hydrogen gas at 700b = ~23.10-3 m^3

The constraints exerted on the container impose the use of type IV cylinders (reinforced), and therefore a weight on-board more important than for hydrocarbons:

- 350bars: 13kg of tank weight per kg of H_2 stored
- 500bars: 17kg of tank weight per kg of H_2 stored

AUVs are much more complex since, not being linked to the surface, they must have energy autonomy and decision-making autonomy enabling them to accomplish their mission.

3.1. MAIN RISKS OF HYDROGEN

Just like other combustible gases or energy sources, handling hydrogen involves risks, particularly ignition and explosion. It presents certain physicochemical characteristics which, by several aspects, facilitate or complicate the control of these risks compared to other gases and liquids:

a) Flammable and explosive nature of hydrogen:

- ✓ Flammability range in air: 4 to 75% by volume (compared to 5 to 15% for methane).
- ✓ Auto-ignition temperature in air: 585°C.
- ✓ Minimum ignition energy: 20 µJ (equivalent to a human electrostatic discharge) against 300 µJ for methane.
- ✓ Rapid combustion, promoting the phenomenon of deflagration.
- ✓ Flame not very visible and not very radiative.
- ✓ A lower probability of explosion in the open air given a high diffusivity which reduces the risk of formation of an explosive cloud in an unconfined environment.

b) Main risk: leaks

The dihydrogen molecule, small in size and low viscosity, has a greater propensity to leak. However :

- ✓ If leak at low flow rate in an unconfined environment: dissipation in the air
- ✓ If high flow rate leak and/or confined environment: accumulation = danger

The installation of a vent system and effective ventilation allows leaks to be dispersed outside the confined space and thus to control the risk.

3.2. H_2 STORAGE SOLUTIONS

Several solutions for the transport and storage of hydrogen currently exist, at different degrees of maturity:

✓ Solid storage: at ambient temperature and pressure by absorption by metal alloys to form metal hydrides. This solution is currently not sufficiently mature for use in the maritime sector.

✓ Liquid storage in cryogenic form: hydrogen cools to -253°C allows storage at atmospheric pressure. The technical and safety constraints linked to these low temperatures do not currently allow this solution to be considered in the maritime sector.

✓ Liquid storage under pressure and temperature close to ambient values – LOHC (Liquid Organic Hydrogen Carrier) process: this solution is still at the development stage.

✓ Storage under pressure: pressurizing hydrogen makes it possible to increase its density and is currently carried out at pressures of 50 to 700 bars. This solution is currently available for applications in the maritime sector.

H_2 bottles

The hydrogen storage pressures envisaged for the maritime sector are 350 to 700 bars. The most used bottles are type 4 cylinders: polymer liner surrounded and reinforced by fiberglass or carbon composite materials.

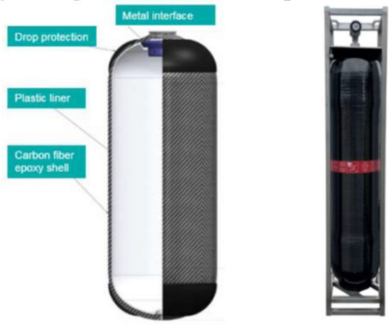

Fig.1. Hydrogen type cylinder - section view; example of storage rack

The bottles are installed in racks, horizontally or vertically. Placed outdoors, this rack must be surrounded by a protective casing against shocks. It must also be equipped with a clarinet for connection to the on-board network.

3.3. H_2 POWER GENERATION EQUIPMENTS

Fuel cells (PAC)

Several types of fuel cells are currently available on the market or in development. For marine hydrogen applications, we mainly note the following technologies:

1. SOFC – Solid Oxide Fuel Cell:

These PACs are used mainly in stationary applications and currently under development for maritime applications. The regulations are preparing to take this type of PAC into account. They operate at temperatures between 400°C and 1000°C and tolerate more varied and less pure fuels than the PEMFC cell.

The efficiency of these batteries is currently between 50 and 60%.

2. PEMFC – Proton exchange membrane

These are the most widely used heat pumps in transport applications operating at low pressure and low temperature (200°C maximum). The efficiency of these batteries is around 50%.

Currently PEMFC technology is more advanced for marine applications (several models currently being certified by classification societies, several ships or boats equipped, significant feedback in mobility applications) and operation at low temperature brings undeniable advantages in terms of safety despite lower efficiency.

Within the proton exchange membrane fuel cell (PEMFC) family, several types of cells exist:

- ✓ So-called low pressure PEM batteries, operating at air supply pressures of the order of a few hundred millibars with a simple air circulator. This technology allows very stable operation of the battery but with lower responsiveness to load variations. On the other hand, it extends the life of the battery.
- ✓ PEM batteries with forced air injection by compressor or turbocharger at pressures of around 1.5 to 2 bars. This technology provides better responsiveness and better efficiency to the battery. The lifespan is shorter and this technology requires more substantial and more energy-consuming auxiliaries.
- ✓ HT-PEM (high temperature) batteries, operating at temperatures of around 200°C. They have better efficiency (50-60%) and are less sensitive to hydrogen impurities, but have a lower energy density and are less widespread today.

a) b) c) d)

Fig.2. Fuel cells: a) 70kW REXH2 V2 (Source: EODev); b) 50kW PM400 (Source: Proton Motor); c) 200kW FCWave (Source: Ballard); d) 200kW Marine System 200 (Source: Power Cellution)

Generally speaking, the different PEMFC heat pump solutions available for maritime applications have the following characteristics:

- Certified for maritime: up to 2MW (Series-parallel connection of heat pumps).
- Average efficiency: 50% (Heat engine: ~35%).
- Optimal load: between 50% and 85% of maximum power.
- Hydrogen quality required as input: ISO14687 Grade D (>99.99%).
- Required inlet air quality: humidity <95%, integrated air filter.
- Preferred operation: operation at constant load, limit stops/starts.
- PAC accompanied by a set of batteries.
- Lifespan: from 4000 hours to 20,000 hours depending on the suppliers.
- Output up to 750VDC by series connection of heat pump.

Fuel cells consist of several modules placed in series to achieve the required power and output voltage. Auxiliaries such as inlet air filtration system, internal control system and output voltage transformer are integrated into the enclosure. Figure 3 shows the components of the PAC PM400 Proton Motor. The energy recovery and produced water systems are not integrated.

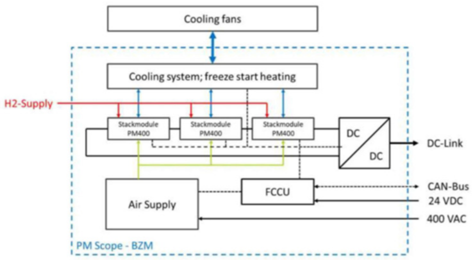

Fig.3. Hydrogen Fuel Cell System (Multi Stack System) - Source: Proton Motor

H_2 engines/ Dual Fuel

Today there are internal combustion engines specifically adapted for the combustion of hydrogen either in dual fuel mode (25% diesel + 75% hydrogen) or in 100% hydrogen mode.

To date, only one supplier has been identified for maritime applications, and only for ranges of semi-fast engines (powers from 1000 to 2670 kW).

Other engine manufacturers announce that they are working on the development of fast engines to make them available for maritime certification within 2 years.

3.4. INTEGRATION OF PAC H2 SYSTEM ON BOARD

Regulation

The various regulations specify in particular the following provisions for the integration of hydrogen systems on board:

- Compressed hydrogen storage

Primary fuel storage must be separated from the heat pump room and must not be placed in an enclosed space, unless special arrangements are made.

It must be located at a minimum distance of B/5, or 11.5m from the wall plating and B/15, or 2m, from the bottom plating of the ship, and aft of the collision bulkhead for cargo ships .

If placed outside on deck, its location must allow sufficient natural ventilation to allow gas dispersion.

It must be equipped with a safety valve and a vertical degassing mast, the end of which must be at a minimum of B/3 or 6m above the work and circulation areas, and 10m from the entrances. and air outlets and inlets to facilities.

It must be protected against mechanical shock.

- Pipelines

The pipes must be placed at a minimum of 800mm from the plating and be equipped with an inerting and leak detection system, as well as a double-skin ventilation system. They must be protected against mechanical shock and include the fewer connections possible.

- Fuel cells

The fuel cells must be located in a dedicated room of the ESD (Emergency Shut type Down), with a redundant ventilation system.

When the PAC system serves as a source of energy for propulsion or essential services, it will be appropriate to install several heat pumps in different separate premises and/or to integrate other energy sources on board.

The heat pump room must be accessible directly from the outside, except for special provisions. Its fire insulation must be type A60.

- Dangerous areas

The definition of dangerous areas of a PAC system is presented in BV NR547.

The ATEX zoning level of each space will be determined by the risk study. These spaces include:

-The refueling space

-Fuel connection and transformation spaces (relaxation)

-The heat pump room(s)

-The ins and outs of the ventilation systems of the different spaces as well as the ins and outs of the vent lines.

Inside these dangerous areas, equipment presenting a risk of spark or heat source important must be certified (ATEX – Anti explosive). This equipment can for example be: motors electric, valve actuators, hydraulic motors, motorized valves, etc.

Figure 4 below shows a typical synoptic view of a PAC H_2 system on board a ship.

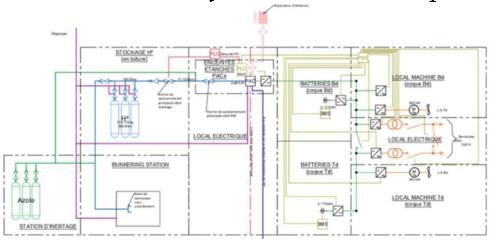

Fig.4. Propulsion synoptic – Example Maritime Shuttle Mont Dore – Nouméa

Note :

- The possibility of operating with a main DC (Direct Current) or AC (Alternating Current) bus for connecting different sources to the electrical network and supplying the main consumers (propulsion).

- The separation of premises, each having their own ventilation, control and security system: premises electrical, heat pump room, battery room, propulsion machine room, inerting station.

From a safety point of view, the following equipment will be integrated (non-exhaustive list):

- PRD type isolation valves storage outlet / PAC inlet.

- Flow limiters.

- Local storage / local heat pump vent lines.

- Thermal camera fire detection devices / "Deluge" type fire fighting device.

- Adapted ventilation storage room / heat pump room with catalytic sensor for H2 detection.

- Pipe inerting system (nitrogen).

4. CURRENT DEVELOPMENTS

4.1. World's first liquid hydrogen ferry

Norled has just launched in March 2023 its very first liquid hydrogen ferry in Norway. Capable of carrying up to 80 vehicles and 299 passengers, this vessel, more than 80 meters long, uses two 200 kW hydrogen fuel cells supplied by Ballard and a 1.36 MWh battery pack from Corvus Energy. It was Linde which, in addition to supplying the green hydrogen necessary to power the ship, ensured the construction and installation of the tanks, a sort of large "thermos" storing liquefied hydrogen at -252.87° C

Fig.5. MF Hydra – first liquid hydrogen ferry (Source: Norled)

Delivered several months ago, the MF Hydra carried out numerous tests at the dock, then at sea before obtaining the final authorizations to begin its commercial operation. Designed by LMG Marin, it now provides a connection between the ports of Hjelmeland, Skipavik and Nesvik, in the west of the country.

4.2. Hylias: Bretagne at the forefront of the hydrogen boat

Under study for more than 2 years, Hylias is at the forefront among medium-sized hydrogen boats for passenger transport. Its service would begin in 2024 in the Gulf of Morbihan. Its size suggests that it could quickly be available in several hundred units for very different uses.

With an aluminum hull 24 meters long, Hylias would carry between 150 and 200 passengers between Vannes and the island of Arz from 2024: 111 on the main deck and 70 on the upper deck. For its propulsion, it would have two motors with a maximum individual power of 130-150 kW (110 kW nominal). Each would drive its own shaft line which would end in a 4-blade propeller with a diameter of 1 m. Not counting the bow thruster.

Fig.6. Hydrogen boat for passenger transport (Source: Hylas)

The ship would carry 2 batteries with an energy capacity of 120 kWh each, and 2 fuel cells (2 x 125 kW). The latter would be supplied by 16 tanks capable of individually receiving 7.5 kg of green hydrogen at a pressure of 350 bars. These containers would be distributed in 2 identical skids pre-assembled and designed to facilitate assembly and maintenance.

4.3. Fresh: A floating solution to supply green hydrogen

Louis Dreyfus PL has just received approval in principle from the Korean Register classification society for a solution for the transport, production, storage and distribution of hydrogen from carbon-free ammonia.

Fig.7. FRESH type vessel (Source: Louis Dreyfus PL)

The type of ships that the company specializing in port logistics services intends to industrialize and market from 2025 is not just a simple boat for transporting ammonia to later make green hydrogen. The concept supported by Louis Dreyfus Ports and Logistics is presented as a floating solution capable of producing the famous gas internally from liquid ammonia. Thus, it could be used, for example, to supply large ships running on hydrogen at sea or around large ports. Both with this ready-to-use gas and with ammonia if customer ships are equipped to use this product directly.

Fig.8. FRESH type vessel - section view (Source: Louis Dreyfus PL)

Could we imagine talking about "last mile delivery" for a Fresh type vessel (Floating Renewable Energy Solution for Hydrogen vessel)? The Korean classification society does not hesitate to use, for this program, the expression "a revolution in last mile logistics in hydrogen delivery".

If Louis Dreyfus PL appealed to Korean Register to obtain approval in principle, it is quite simply because the current normative classification rules are not sufficiently extensive for the innovation that the Fresh solution constitutes. With the assessment provided by the Korean company, project leaders can be reassured regarding the safety and technical viability of their hydrogen transport, production, storage and distribution vessel.

6. CONCLUDING REMARKS

There is still a way to go to motorize cargo ships weighing several thousand tonnes, especially since storage and safety issues must be resolved. For bunker storage, projects still vary between compressed hydrogen and liquid hydrogen, the latter solution having the advantage of a much higher energy density, therefore a lower occupied volume, but being more complex to implement.The characteristics of hydrogen differ greatly from those of natural gas, requiring a new approach, highlighting the current uncertainties about the behavior of liquid hydrogen (LH_2) and the thresholds at which an explosion occurs. In the event of a leak, jets of hydrogen or residual pockets could be created.

Having explored the different avenues that are opening up, from the use of hydrogen in combustion engines to the mixing of hydrogen with other fuels, we can conclude that the fuel cell remains the most advanced technology, effective in terms of performance before also recognizing that this is today limited to small coastal vessels.

In conclusion, 3 obstacles remain to be overcome before hydrogen can power medium and large tonnage vessels:

-that green electricity sources have sufficient power to power future electrolyzers,

-that fuel cell technology allows powers of several tens of MW in a reasonable volume,

-that risk analyzes have defined the rules for the storage and use of hydrogen on board long-haul ships.

Long-term optimism is required, but the deadlines are still uncertain.

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