Conceptual design of a hybrid propulsion vessel for transporting green hydrogen to aquaculture farms

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Abstract

This work describes the conceptual design process of a vessel intended to transport green hydrogen to aquaculture farms in the Aysén Region, Chile. The design proposes a hybrid power generation configuration, which integrates PEM fuel cells (PEMFC) and a battery bank, to ensure efficient and continuous operation. Within the propulsion system, the implementation of an azimuthal Z-drive system is established, enhancing maneuverability for efficient operations in the cultivation centers. The process includes an exhaustive analysis of the ship's mission profile, together with improvements in hull design, evaluating the forward resistance by means of computational fluid dynamics (CFD) simulations. Power demand under different sailing conditions is also considered, with the objective of optimizing the power generation capacity of the plant and the hydrogen storage required for the propulsion and transport system. The development of this work is part of the PT02 project at the Sustainable Acceleration Center for Electromobility (CASE).

Key words: Hybrid propulsion, hydrogen storage, hydrogen regulations, maritime transport, hull optimization, CFD analysis, power demand balance.

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Introduction

Presentation of the topic

The growing demand for sustainable alternative energies in maritime transport has driven the development of new technologies aimed at emissions reduction and energy efficiency. Among these alternatives, green hydrogen emerges as a clean and viable energy source, especially in regions with abundant renewable resources for its production. This work focuses on the hull design of a hybrid propulsion vessel optimized for the safe and efficient transport of green hydrogen to aquaculture farms.

The design of a ship's hull form plays a key role in a naval project, which must consider studies that allow the ship to meet functional, operational and safety requirements. In addition, the ship's energy consumption must be optimized to maximize autonomy and optimize space for the power generation and propulsion system equipment, as well as for the habitability of the personnel who will oversee transporting the hydrogen. Technological developments present an opportunity to drive the transition to clean energy in cultivation centers, mitigating the environmental impact on the maritime industry.

In this context, the present study analyzes the necessary design criteria for hull shapes, evaluating the integration of the hybrid propulsion system combining the use of PEM type fuel cells with battery banks. The area of operation and the mission profile define the hull shapes of a ship for a naval project, thus establishing the studies that will be seen in the present work so that the ship can safely transport clean energy.

Objectives

The main objective is to design a vessel concept for efficient and safe maritime transport of hydrogen to the aquaculture farm centers. The specific objectives are as follows:

- Select the navigation route and operating speed of the vessel.
- Establish the configuration of the power generation system.
- Optimize the ship hull shapes through CFD analysis.
- Determine the ship propulsion system.
- Calculate the power requirements of the propulsion engines.
- Calculate the power generation demand.
- Calculate the hydrogen required for power generation on the vessel and for transport to the aquaculture centers.

Justification

The project focused on advancing in the incorporation of technology associated with electromobility in maritime transport, through the design of a hydrogen transport vessel, as well as its use for the propulsion and auxiliary systems.

The new environmental requirements and the constant concern of aquaculture (salmon farming) producers to improve the quality of their production and logistics systems require the use of non-polluting fuels in the fish farming centers at sea and the vessels that provide services associated with the installation of farming centers and the transport of supplies (materials, fish feed, personnel transport and fuels), considering that they currently consume fossil fuels.

There are approximately 1027 operational vessels providing support services to the aquaculture industry in Chile, which have power generation systems for propulsion systems, with power ranging from 50 kW to 1 MW *(Sernapesca, 2024).*

Currently, there is a very low adoption of technology associated with electromobility on vessels that provide services in aquaculture. This situation is related to the gaps identified in the terms of the center's call for proposals:

- Transformation of internal combustion

vehicles to electric (fleets) for specific functions. By transforming the power generation system from ships to hybrids.

- This can be addressed by developing digital solutions for monitoring and control, through the adaptation and development of practical applications. By developing a computerized system for control and evaluation of the hybrid power generation system.
- In addition to the above, at present (year 2024), salmon farming companies are working on the incorporation of H2G into the energy matrix of fish farming centers, for which they need vessels capable of transporting H2G safely to these centers.

Methodology

The methodology used in the present work is as follows:

1. Project Development: This project follows a structured methodology that combines theoretical analysis, design, simulation and energy performance evaluation. The overall approach focuses on the application of electromobility concepts and the use of green hydrogen in the design of a hybrid ship. The different methodological steps were implemented to ensure an effective integration of sustainability and efficiency objectives in the final ship design.
2. State of the Art Study: A comprehensive review of the literature and previous studies on the use of fuel cells, hydrogen as a fuel and hybrid propulsion systems applied in ships was conducted. This review included recent research on the application of clean technologies in the maritime industry. In addition, regulations that allow hydrogen to be safely stored and transported in a vessel were analyzed.
3. Design Proposal: Based on the findings of the state of the art, a preliminary hull and propulsion system design was proposed that incorporates energy efficiency features and safe hydrogen storage capacity. This design considered factors such as energy demand under different operating conditions. A hybrid propulsion configuration was selected that integrates hydrogen as the primary source of energy through PEMFC's and the implementation of battery bank to handle the load variation of the power generation system. Thus, fossil fuels are completely excluded from the design in the study, considering only clean energies.
4. Numerical Simulations: To evaluate the performance of the proposed design, numerical simulations were performed using CFD software. These simulations allowed analysis of the hydrodynamic resistance of the hull, to determine the thrust required by the propellers. From this analysis, the required brake power for the ship's engines was obtained, which contributes to validating the performance of the propulsion system and ensures its efficiency in operation.
5. Energy Balance: Finally, an energy balance was performed that considered the ship's energy needs and the estimated hydrogen consumption in its operations. This balance allowed defining the optimal configuration of the hybrid propulsion system, evaluating the amount of hydrogen required by the PEMFCs in the ship, the size of the storage system and the power demand in different operating scenarios to identify the most energy demanding scenario. This maximum power demand is determined from the sum of the loads, which include the propulsion system, auxiliary systems and general services. This evaluation ensures that the design meets the power requirements under maximum load conditions and guarantees optimum performance in all anticipated operating situations.

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Definition of design requirements

The design requirements in a naval project must include elements of the mission profile, area of operation, main dimensions, available spaces for equipment, habitability and cargo, autonomy and equipment layout for its operation. This allows the ship to meet functional, operational and safety requirements.

Then, according to what has been defined in the current stage of the project, Fig. 1 shows the scheme of hydrogen production, compression, bottling, transportation and use for the cultivation centers. Hydrogen production will be carried out at the Piscicultura Fiordo Aysén (PFA), located in the Aysén Region, Chile. The PFA has daily production (through electrolyzers) of 300 kg of hydrogen that will be compressed in bottles and consumed for the generation of electricity in the 6 cultivation centers through PEM fuel cells (PEMFC), each consuming 80 kg of hydrogen per day. The method of supplying hydrogen from the PFA to the cultivation centers is by transporting hydrogen in a ship that is designed for that purpose.

Navigation route and ship dimensions

The ship's mission profile is to transport hydrogen cylinders from the PFA to feed pontoons that consume hydrogen for electricity generation (PEMFC).

Fig. 2 shows the navigation route of the ship, covering 18 NM from Puerto Chacabuco to the PFA, and another 18 NM returning from the PFA to Puerto Chacabuco, resulting in a total travel distance of 36 NM with a trip duration of 6 hours at a speed of 6 kn or with a duration of 4.5 hours at a speed of 8 kn if considered at maximum ship's speed, while the ship transports hydrogen to the cultivation centers near the navigation route of the ship. It is established in the present work to consider the maximum navigation speed (8 kn) as a study parameter to ensure the maximum operating condition of the ship.

The ship operates 8 hours a day, this duration is set on the ship’s 4.5 to 6 hours of navigation time, 2 hours allocated for maneuvering or bunkering conditions, and the rest of the day remains docked at Puerto Chacabuco or PFA, connected to the shore power grid. A 3-day autonomy is established for the ship, generating power from its power plant for a total of 24 hours spread over these 3 days, supplying energy to the propulsion system, general services, and auxiliary systems to meet its mission profile.

Table 1 presents the technical specification of the vessel, highlighting its main structural and performance characteristics. This vessel has an overall length of 23 meters and a beam of 8.5 meters, with a displacement capacity of 155 tons. It is equipped with two propulsion engines of over 100 kW each, reaching a maximum speed of 8 knots and an operating range of 3 days.

Power generation system configuration

A fully electric propulsion configuration based on a hybrid combination of a PEMFC, and a battery bank is implemented. This

Fig. 1. Hydrogen production, compression, bottling, transportation and use for the cultivation centers.

Fig. 2. Navigation route of the ship.

Table 1. Parameters and definition of ship requirements.

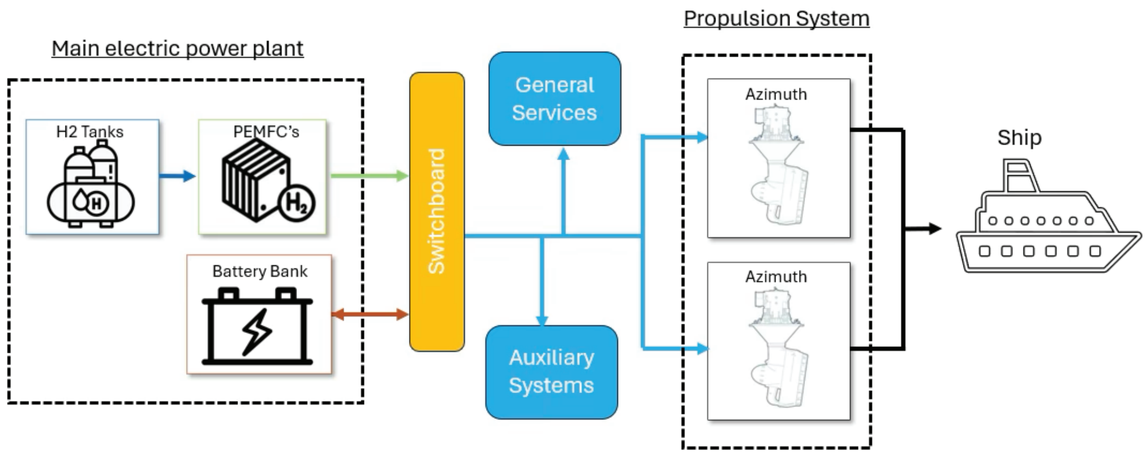
Parameter	Value	Unit
Total length	23	m
Beam	8.5	m
Depth	2.4	m
Minimum draft	1.3	m
Maximum draft	1.7	m
Gross tonnage	<100	-
Displacement	155	ton
Propulsion motor quantity	2	-
Power per motor	>100	kW
Nominal speed	6	kn
Maximum speed	8	kn
Autonomy	3	days

setup leverages the advantages of both energy sources to optimize performance and operational sustainability. Power generation relies solely on the PEMFC, which implies significant hydrogen consumption to meet regular operational power demands.

To maximize system efficiency and ensure stable power delivery, the PEMFC must operate consistently within its optimal range, maintaining steady performance and avoiding overload or low-load conditions that could shorten its lifespan. The battery bank plays a crucial role in this configuration, acting as a buffer that smooths out fluctuations in power demand. This allows the PEMFC to operate under ideal conditions, extending the system's lifespan by minimizing abrupt variations in power generation.

Given the high hydrogen consumption that this configuration entails, careful planning is essential for both hydrogen storage and supply. Hydrogen availability must be constant and reliable to support continuous operation, necessitating high-capacity storage systems and efficient supply strategies. Additionally, optimizing the efficiency of each

Fig. 3. PEMFC and battery power generation system configuration.



system component is crucial to reduce losses and improve autonomy, thereby ensuring continuous and safe operation under this hybrid propulsion scheme.

Engineering analysis and optimization of vessel design using computational tools

This section optimizes the hull design, calculates ship resistance, defines the propeller type and estimates the required engine brake power. These analyses allow fine-tuning of the hydrodynamic performance and selecting the most suitable propulsion system to meet the vessel's operational requirements.

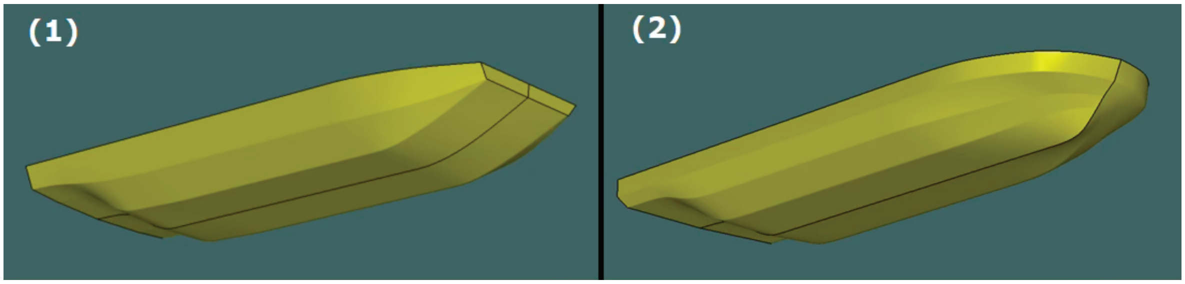
Ship resistance

Hull optimization focuses on minimizing resistance optimization by reducing the ship's resistance, and therefore reducing the power required from the propulsion engines. Ship resistance is the force that opposes a ship to move forward at a constant speed, depending mainly on the forward speed and the ship shapes, this parameter allows to determine the power of the engines required for propulsion *(Huenante, 2018)*.

For the optimization of the bow design, it should cut the water with less effort, since the objective is to reduce the frontal surface that is exposed to direct impact with the water, facilitating the smooth deflection of the flow along the hull. Fig. 4 shows the hull (1) with a flat bow that has a larger surface area in direct contact with the water, which causes an increase in water pressure on the bow. Fig. 4 shows that the hull (1) of the ship had a 3-surface design, resulting in a less efficient distribution of hydrodynamic forces, particularly in the bow area and the lateral parts of the hull. It was considered for the redesign on hull (2) to incorporate 4 surfaces, improving the transition between the different areas of the hull for a more homogeneous distribution of water pressure. It was considered to maintain the enclosed volume when modifying the hull (1), because in Chile ships are classified according to gross tonnage (measure that quantifies the total internal volume) in larger and smaller ships. The latter is subject to less strict regulations compared to a larger vessel, therefore, it is important to control the total enclosed volume of the ship.

Fig. 5 shows the results of the hull (1) systematic series and CFD simulations of the hull (1) and (2), considered at a maximum draft of 1.7 m. The results in Fig 5 are the sum of hull resistance by systematic series

Fig. 4. Ship hull design 1 and 2.



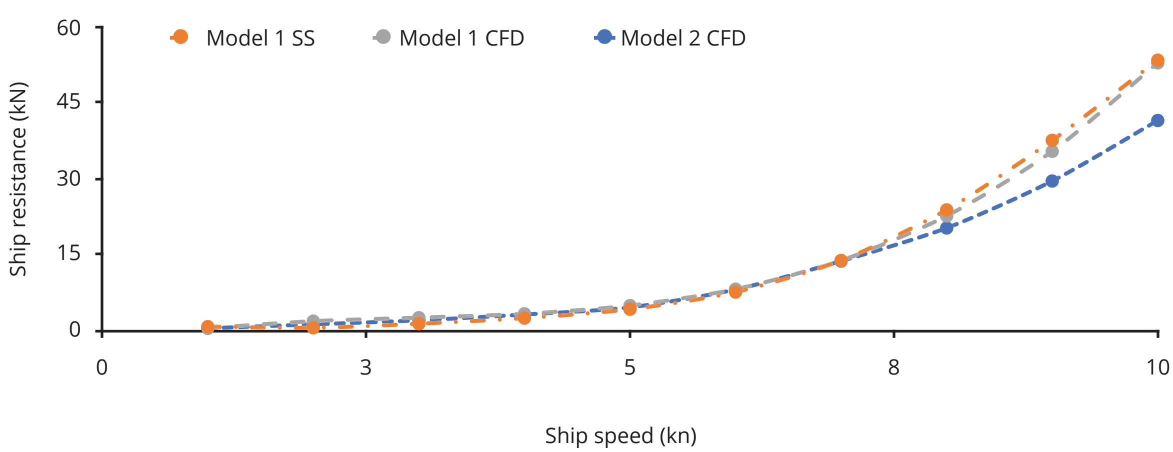
or CFD simulation, resistance by appendage, resistance to air and a safety coefficient of 5% to be added in case of an eventual increase in resistance due to fouling. The results of hull simulation (1) are validated against the systematic series, showing a maximum percentage difference of 5% at a speed of 9 kn. When compared to the results of hull simulation (2), the latter demonstrates lower ship resistance in the speed range of 7 to 10 kn. In this way, the use of the hull (2) is established for further studies due to lower resistance at a speed of 8 kn compared to the hull (1), presenting a difference of 15% of the ship resistance.

Ship propeller

The propeller is the typical propulsive element of ships, and is based on the physical phenomenon of lift, where the movement of a propeller blade in a fluid, due to the action of the propeller, generates a thrust on the blade whose component about the longitudinal axis of the ship can be used to produce the forward motion of the ship *(ABC Puerto, 2021).*

It was established to implement azimuth thrusters on the vessel to improve maneuverability and allow a more precise and controlled approach to the crop centers. These thrusters consist of propellers that can orient their thrust by rotating around a vertical axis through 360°, eliminating the need for a conventional rudder. Their design allows the electric motor to be coupled perpendicularly to the propeller in a container, without requiring a rigid shaft line (Castorani, 2016). These electric motors are powered by alternators located in the engine room, thus optimizing control and efficiency in approach maneuvers. In addition, this allows the engine room length to be reduced from 6 m to 3 m, allowing power generation equipment

Fig. 5. Results of total ship resistance.



and accommodation to be more efficiently distributed along the length of the vessel below deck.

The choice of a Z-drive type azimuth thruster for a 1500 mm stern height is due to the mechanical and structural advantages offered by this system in configurations with less vertical clearance. The Z-drive has a “Z” gear connection, which allows the motor and propeller shaft to be vertically decoupled. This type of drive allows for advanced maneuverability and a compact design that fits well in limited spaces, maximizing vessel control without the need for significant structural modifications to the stern.

An initial estimation was carried out at a speed of 8 kn to size the ship's propellers, selecting a diameter of 950 mm, 3 blades and a blade area ratio of 0.4, according to the characteristics of the Wageningen B series, this series provides a set of empirical data that allows predicting the hydrodynamic performance of propellers. This depends mainly on the thrust generated by the propellers, calculated as a function of the ship resistance shown in Fig. 5. Since the propulsion system has two propellers, the thrust required to overcome ship resistance is divided between the two propellers, so that each propeller contributes to equalizing the ship resistance at the evaluated ship speed. With this configuration, an overall propulsive efficiencyof 52% was obtained, which is adequate for the speed and operating conditions of the vessel. Also, a minimum brake power of 100 kW per engine was calculated, this value considers the performance and mechanical efficiencies of the propulsion system.

Ship power demand

In this section, the ship's power demand balance is carried out, considering five operating conditions, as shown in Table 2. These conditions will be analyzed to identify the one with the highest consumption and verify that the power generation plant can supply the necessary power to meet the ship's requirements.

Then, according to Table 2, the following points are established:

- The power factor is 0.8 for ships and 20% is considered the safety coefficient for total power demand, because 10% is an overestimation and the other 10% for future modifications in power demand *(Klebanoff, 2020)*.
- The navigation condition (8 kn) is established as the highest power demand with approximately 277 kW.
- Two PEMFC's of 150 kW each are used, with the capacity to deliver power in the ship's highest power demand condition (navigation), delivering a total power for the PEMFC's of 300 kW.
- A redundant PEMFC is considered in case of any failure.
- The PEMFCs experience transient or low loads in maneuvering or bunkering conditions; therefore, they will be supported by a battery bank preliminarily and conservatively sized according to the power demand of 58 kW in bunkering conditions, with a 30% safety factor for 2 hours daily, allocated for maneuvering or bunkering conditions. This results in a battery bank capacity of approximately 150 kWh.
- The PEMFCs experience transient ship speed variation; therefore, they will be supported by a battery bank preliminarily and conservatively sized according to the 30% power demand of 278 kW in navigation conditions, with 84 kW for 2 hours daily. This results in a battery bank capacity of approximately 168 kWh.
- The capacity of the final battery bank is 320 kWh, which considers the maneuverability/bunkering condition and ship speed variation condition.

Table 2. Power demand for ship service conditions.

Load situation	Port (0 kn)	Maneuver (1-2 kn)	Navigation (8 kn)	Bunkering (0 kn)	Emergency
Propulsive system (380 VCA)	0,00	13,00	206	0,00	0,00
PEMFC auxiliary system (220 VCA)	13,66	13,66	13,66	13,66	0,00
Ship services (220 VCA)	3,90	1,95	1,95	3,90	1,50
Deck equipment (220 VCA)	21,60	0,00	0,00	21,60	0,00
Ventilation (220 VCA)	0,38	0,38	0,38	0,38	0,38
Hotel (220 VCA)	7,39	7,39	7,39	7,39	0,00
Lighting (220 VCA)	0,28	0,28	0,28	0,28	0,36
Navigation (24 VCD)	0,22	0,22	0,22	0,22	0,28
Control and communications (24 VCD)	1,24	1,24	1,24	1,24	1,24
Total power (kW)	48,69	38,14	231,14	48,69	3,76
Power factor	0,80	0,80	0,80	0,80	0,80
Total apparent power (kVA)	60,86	47,67	288,92	60,86	4,70
Total power 20% SF (kW)	58,42	45,76	277,36	58,42	4,51
Total apparent power 20% SF (kVA)	73,03	57,20	346,70	73,03	5,64

Hydrogen storage for propulsion and transportation

At ambient temperature, hydrogen exists as a gas and due to its low energy density per unit volume (12MJ/m^3), hydrogen gas is normally stored under high pressures, in the range of 175 to 1000 bar. Under such conditions, the use of specially constructed type IV pressure vessels has been successfully used to store high pressure hydrogen. This type of pressure vessel is made of an inner liner of plastic material (high density polyethylene), reinforced with glass or carbon fibers that cover the entire plastic liner, supporting all structural loads. The outermost part is coated with fiberglass to protect the external surface and withstand pressures not exceeding 700 bar. Unlike other containers in which its material is steel, this makes it lighter, which leads to less weight on the ship, and less power required by the propulsion engines *(Santiago, 2022)*.

UAC works with cylinders at pressures between 200 to 350 bar and the capacity of hydrogen that can be stored in a cylinder is in the range of 40 to 46 kg, depending on the selected length of the cylinders *(UAC, 2018)*. Considering the space available above deck to store the cylinders, a 350 bar cylinder is selected, with a hydrogen mass capacity of 40 kg and an estimated weight of the cylinder itself of 1 ton. UAC also offers hydrogen transport modules, consisting of UAC Type IV fiberglass pressure vessels, fixed in standard

ISO or High Cube modules, or in MEGC hook-loading containers *(UAC, 2018)*.

PEMFC hydrogen requirement

In this section, the goal is to determine the amount of hydrogen required for ship energy demand, based on the power supplied by the PEMFCs as shown in Table 3. The PEMFC has a total operating time of 24 hours, of which 8 hours per day will be used to propel the vessel. This provides an autonomy of 3 days, allowing the vessel to operate continuously during this period without the immediate need for hydrogen refueling.

Table 3. PEMFC requirements.

Parameter	Value	Unit
Power (P)	150	kW
Number of PEMFC (N)	2	-
Operation time (t)	24	h
Fuel cell efficiency(η)	0.5	-
Lower heating value (LHV)	120.000	kJ/kg

The calculation of hydrogen required by the PEMFC's to meet the mission profile of the ship is performed, according to the following formula *(Marine Service Noord, 2024)*:

$$Hydrogen\ \ amount = \frac{P*t*3600}{\eta*LHV}*N \qquad (1)$$

$$\therefore Hydrogen\ \ amount = 432kg$$

Hydrogen storage summary

Then, depending on the selection of UAC's Type IV hydrogen cylinder, the following is determined:

1. It establishes the use of a type IV cylinder that stores 40 kg of hydrogen at 350 bar, with a length of 5720 mm and a diameter of 750 mm.
2. It establishes the use of 20' ISO Standard size containers (6.1 x 2.44 x 2.59 m) that stores 9 Type IV cylinders.
3. For the transport of hydrogen (cargo), 3 ISO Standard 20' containers will be provided on the deck of the ship, with a total of 1440 kg of hydrogen for this purpose.
4. Considering that there are 6 cultivation centers, and each one consumes 80 kg of hydrogen per day, then 240 kg of hydrogen are transported to each cultivation center. And that the transportation is carried out by the ship during the 8 hours of operation of the ship during the day.
5. The required amount of hydrogen for PEMFC units to fulfill the mission profile is summarized at 432 kg. This hydrogen is stored in 12 type IV cylinders and will be available below deck, each with a capacity of 40 kg, providing a total of 480 kg of hydrogen across all cylinders.

Conclusions

The following points are concluded:

- The optimization of the hull design resulted in a 15% improvement in hull efficiency (2) at a maximum speed of 8 knots, which significantly contributed to the reduction of resistance and, consequently, improved the ship operational efficiency.
- The use of azimuthal thrusters enhanced the vessel's maneuverability while reducing the engine room space from 6 meters to 3 meters, allowing for better space distribution on board and improving both habitability and design flexibility.
- The hybrid configuration of the power generation system, combining PEMFCs and a battery bank, was key to meeting the vessel's energy demands. The total generation power was set at two 150 kW PEMFCs and a 320 kWh battery bank, ensuring that the system covers power variations under all established conditions.

- A more detailed analysis of the battery bank capacity is essential to ensure optimal performance under various operating conditions, such as speed variations, maneuverability and bunkering operations.
- The amount of hydrogen transported to the aquaculture centers is 1440 kg, with respect to the amount consumed by the power generation demand of 480 kg, representing 33% of the total hydrogen on board as consumption.
- The volume allocated for the hydrogen tanks serving the PEMFCs is 110 m³ and the total volume below deck is 350 m³, the space dedicated to hydrogen storage for the PEMFCs accounts for 32% of the total below-deck volume.
- Regarding future research, there are key areas to continue exploring, such as the optimization of bunkering operations and the efficiency of hydrogen distribution and storage, which could improve the system's autonomy and sustainability.

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