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小型船舶基于混合电力推进的能效改进

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摘要：未来小型船舶建造的目标之一是减少船舶排放，以符合国际海事组织（IMO）关于温室气体和污染物排放现行和将来的规定。本文介绍了与船舶对环境影响的相关文献和相关规章。提出了电力推进，特别是混合推进系统（HPS）是减少小型船舶的环境影响的具有前进的解决方案。这些小型船舶常常在人口密集区域附近使用，这些区域是减少污染和排放的非常关键的区域。本文提出了用于小型船舶的几种混合动力和电动推进系统，包括对未来船舶建造挑战的综述，以及可在小型船舶中实施的 HPS 的可能拓扑结构的描述。本文还描述了 HPS 的关键特点，并且介绍了小型电力混合船舶的实例。

关键词： 混合电力船舶；串并联混合；燃料电池；超级电容；二氧化碳排放；电力电能

Improving Efficiency and Emissions of Small Ships by the Use of Hybrid Electrical Propulsion

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***Abstract* -- One of the future goals of shipbuilding for small ships is to reduce the impact of ship emissions to respond to existent and future regulations of the International Maritime Organization (IMO) on greenhouse gas and pollutants emissions.**
This work presents a state of the art of the context and related regulations associated to ship environmental impact. It shows that, electrification of propulsion and particularly Hybrid Propulsion Systems (HPS) are promising solutions to reduce the environmental impact of small ships which are often used near agglomeration areas which are very critical area for pollution and emission. Several hybrid and electric propulsion systems for small vessels are presented. The paper includes a general description of the future challenges for shipbuilding and a description of the possible topologies of HPS which can be implemented in small ships. The key features of the HPS components are also described and examples of small electric and hybrid ships are presented

***Index Terms*-- hybrid Electric ship; series hybrid; parallel hybrid, fuel cell; battery; supercapacitor; CO_2 emissions; electrical power.**

I. Nomenclature

IMO	International Maritime Organization
MARPOL	Marine Pollution
ECA	Emission Controlled Areas Sulfur

II. Introduction

THe transport sector represents about 25% of the total commercial energy consumed in the world [1].
More than 80% of freight is transported by sea, and maritime transportation is responsible of more than 30% of the CO_2 emissions of the transportation sector and about 3% to 4% of the human CO_2 emissions. Greenhouse gas emissions related to ships are important and rapidly growing. Without action, these emissions will be more than double by 2050 due to the expected growth of the global economy and the associated transport demand [2]. This is why stringent international regulations have been established or are in project to limit ship emissions.
In this context, minimization of fuel consumption and reduction of emissions is one of the main objectives for designing future generations of ships [3]. One of the main challenges is to improve efficiency and optimally manage the energy/propulsion chains in order to reduce fuel consumption and environmental impact with an investment as low as possible [4]. In this perspective, electrification and hybridization of the propulsion chains are one of the solutions for the development of more efficient ships and environmental friendly ships [5-6].
In this paper which is an extended version of [7], we will present firstly the global challenges of reducing ship pollution and emissions. We focus in the second part on the hybrid energy for propulsion of small ships. We present the various hybrid configurations and the criteria of choice of the energy generation and storage systems. Indeed, even if in many cases, small ships are devoted to operate in very critical area in terms of pollution (harbor, city, rivers), till today, due to technical and economic reasons, little interest

was granted to electrification and hybridization of small ships.

III. Ships Impacts and Regulatory Aspects

Diesel engines remain currently the most used for ships in conventional propulsion systems as shown in Fig .1

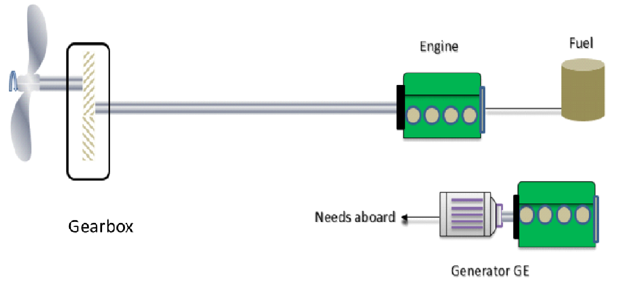


Fig.1: Conventional propulsion schema (传统推进系统结构)

Diesel Engines are characterized by a high level of autonomy compared to other sources. They are however characterized by a high level of greenhouse gases and pollutants emissions, particularly if they work bellow their rated power. The exhaust gases of diesel engines mainly include nitrogen (N), oxygen (O), carbon dioxide (CO_2) and water vapor (H_2O), with small amounts of carbon monoxide (CO), sulfur oxides (SO_x), nitrogen oxides (NOx), hydrocarbons (HC) and particulate matter (PM) [2-3].
Fig. 2 illustrates the emissions of exhaust gases in a diesel engine [8]. As can be noticed, CO_2 is the most part of the pollutant elements rejected, followed by nitric (NO_x) and sulfur (SO_x) oxides.

The emissions of ships are directly related to the rejections of their engines. These emissions are all oil combustion products which can be classified as primary or secondary pollutants [4]. The primary pollutants are pollutants formed directly during the combustion process (sulfur oxide, oxide of carbon, nitrogen oxide…) while secondary pollutants are formed results of chemical reactions in the atmosphere (nitrogen dioxide, ozone, secondary particles…) [5].
Without action, CO2 emissions will be more than double by 2050, due to the expected growth of the global economy and the associated transport demand as shown in Fig. 3 [2].

MARPOL 73/78 adopted by the IMO aims to prevent and mitigate global marine pollution [9]. For example, the annex VI of MARPOL defines strict limitations and emission controlled areas (ECAs) for Sulphur and Nitric oxides covering the English Channel, the North Sea, the North American coast and the Caribbean under US control area as shown in Fig. 4 [10]. In these protected areas (ECAs) the maximum permissible Sulphur content of marine fuels fell to 0.1% in 2015 as shown in Fig. 5. In other areas these Sulphur contents are subject to a limit of 3.5%. This overall limit will probably fall to 0.5% in 2025 while awaiting the results of a review to be completed in 2018. Table 1 gives the NO_x limitations for ship construction, defined by MARPOL VI [2].
The objectives of limiting the environmental impacts are particularly difficult to reach for small ships. Indeed, in one hand these small ships (pleasure boat, tugs, naval buses, river shuttles…) are often used near or in agglomeration areas which correspond to the highest restrictions in terms of pollution and emissions, and in the other hand, in such small boats, the volume and the number of components of the energy chains are strongly limited, reducing the possibilities of implementing innovative energy/propulsion systems. This is why the second part of the paper will focus on the solutions to reduce the impacts of small ships and particularly on the solutions based on electrification and hybridization of the energy chain.

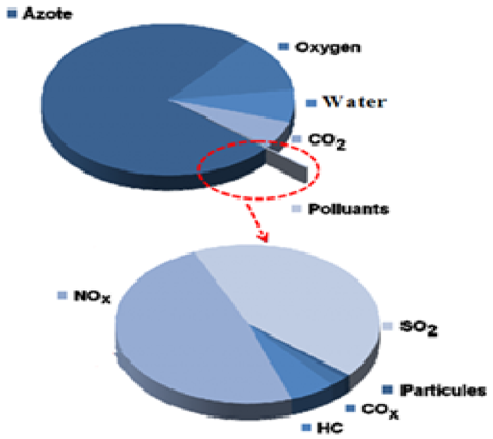


Fig.2: Contents of diesel engine exhaust gas (柴油引擎排放废气) [8]

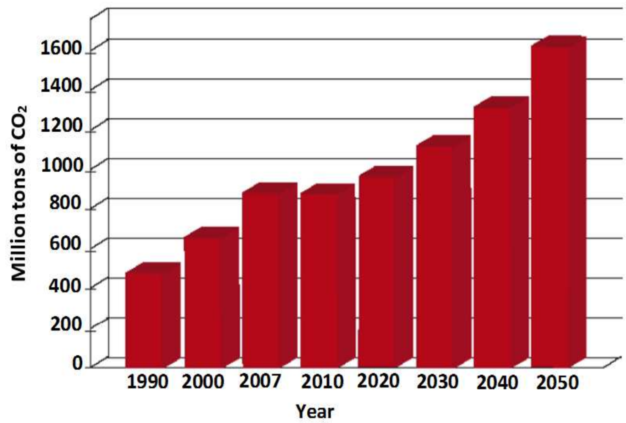


Fig.3. Evolution of CO2 emissions in shipping (船舶二氧化碳排放量) [2]

Fig.4. Emission Controlled Areas for Sulphur (硫排放受控地区) [10]

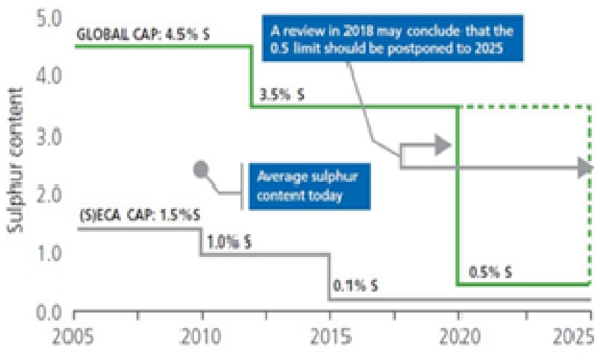


Fig.5. Sulphur content limits through time (硫化物排放限制的发展) [11]

Table 2: Conversion factors for fuel emissions (燃料转换因子) [9]

Fuel type	Kg CO_2/Liter	Kg CO_2/kg
Motor Gasoline	2.8	
Diesel Oil	2.9	
Gas Oil	2.9	
Liquefied Petroleum Gas	1.9	
Compressed Natural Gas		3.3
Jet Kerosene		3.5
Residual Fuel Oil		3.5
Biogasoline	1.8	
Biodiesel	1.9	

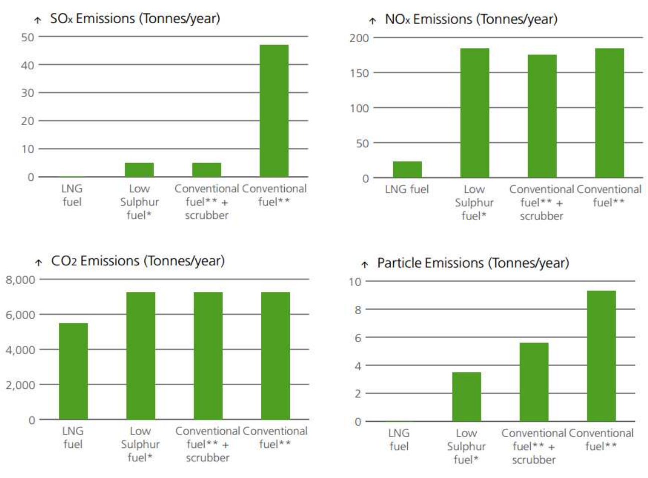
Table 1 : NOx Limitations – MARPOL VI (氮氧化物的排放限值) [2]

Tier	Construction date	NOx Limit, g/kWh n= engine's rated speed (rpm)		
		n<130	130≤n≤2000	n≥2000
I	01 /01/2000	17	$45.\ n^{-0.2}$	9.8
II	01 /01/2011	14	$44.\ n^{-0.23}$	7.7
III	01 /01/2016	3.4	$9.\ n^{-0.2}$	2

IV. Ways of Reduction of Small Ship Environmental Impacts

1) *Reduction of ships emissions by the use of alternative fuels*

Table 2 represents a summary of the different conversion factors of CO_2 emission for different types of fuel [9]. These data underline in particular the interest of biofuels compared to fossil ones. In recent years, the LNG (Liquefied Natural Gas) has been considered as an alternative fuel for ships [13]. Fig. 6 shows a comparison between several types of fuel in terms of emissions. These results shows that LNG is a very interesting alternative to diesel allowing a reduction of about 85-90% of NOx emissions, almost 100% of SOx emissions and about 15-20% of CO_2 emissions.



* Low sulphur fuel contains maximum 0.1% sulphur
**Conventional fuel as per 1 July 2010, containing maximum 1% sulphur

Fig.6. Emissions of different types of fuel for typical ships (典型船舶的排放图) [13]

2) *Electrification and Hybridization of ship propulsion for small ships*

New electric and hybrid propulsion architectures, allowed by innovative and high performance components (batteries, fuel cells, supercapacitors) are a very promising track to strongly reduce pollutants and greenhouse gas emissions. If some studies are conducted for the integration of such architectures in large vessels, small ships benefit only marginally today of this kind of systems. Actually, the integration of these new propulsion architectures on small ships operating on shorts cycles is a real technical challenge. Indeed, in such ships, the volumes devoted to energy storage and energy/propulsion systems are strongly reduced. Furthermore they often operate in transient involving strong power demand. The available times for charging energy systems are also often limited.

In the following, we describe the different hybrid energy/propulsion topologies and give some elements related to the adequacy of these topologies to meet the specific requirements of small ships.

A. *General Advantages of electric and hybrid propulsions*

Hybrid Propulsion Systems (HPS) are interesting when there is a large variation in power demand during operations. The design rules of this type of systems can differ significantly for different types of vessel, mainly due to the different types of mission profiles and operation requirements. Hybrid propulsion systems are very promising technologies to design high efficiency and environmental friendly small ships [14-15].

- HPS provide a better energy efficiency and significant greenhouse gas and pollutants emissions reduction than classical mechanical systems [15-16],
- Hybrid systems are modular, and offer a power redundancy.
- The use of electrical propulsion systems (POD system and thrusters) allow to improve maneuverability with important reduction of noise and vibrations [15],
- Electrical propulsion systems offer more degree of freedom for naval architecture and allows to free onboard available space.
- HPS allows reducing of the level of vibration transmitted to the structure of the ship.

- HPS leads to a reduction of maintenance operations on the combustion engines because the combustion engines are always optimally used.

However, all technologies are not mature and a satisfying compromise between cost, mass, and energy management performance is not yet reached

B. Hybrid propulsion topologies

Hybridization of the propulsion chains is a promising approach to minimize fuel consumption; especially for vessels that requires a high degree of maneuverability and very varied operating cycles [14-17]. It is based on the combination of several different energy sources. The choice of the sources and their combinations is adapted to the ship power and energy requirements which include the needs of low and high power, the needs of flexibility in operating modes and the needs of redundancy and reliability.
Three main HPS architectures are encountered:

- *The Series Hybrid architecture*

In this type of HPS architecture (Fig. 7), two kind of energy system (combustion engines and electric systems) are used in series [16]. The propulsion is done by a variable speed electrical drive (propulsion motor and power converter). The electrical power of the propulsion motor is generally supplied by a set of generators driven by combustion engines. Another option is to use fuel cells to provide electricity or a combination of fuel cells and generators driven by combustion engine. Energy storage systems (ESS) such as batteries, supercapacitors, etc. can be connected to the electrical bus. This ESS can be used separately or with the generators [17].
In this configuration, electricity is used as an energy vector between the combustion engine and the propulsion motor, so there is no direct mechanical connection between the combustion engine and the propeller [18]. This configuration allows dissociating the operating points of the combustion engine and of the propeller. This is why it allows increasing the global efficiency of the system by optimizing the operating point of combustion engine and propeller in efficiency point of view. Of course, this advantage would be more significant if several generators and ESS are used, because it allows providing the required propulsion power by choosing an optimal combination of sources in order to keep the running combustion engines in their optimal operating area. This is why this structure is massively used for high power ships as military or passenger's vessels. However, for small ships, the possibility of multiplying the sources is very limited by volume and mass constraints.

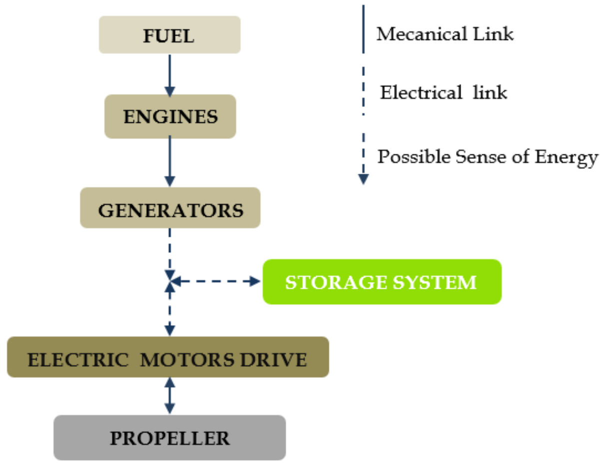


Fig. 7: Typical Series hybrid architecture (典型串联混合推进系统) [19]

- *Parallel Hybrid architecture*

A typical parallel HPS is shown in Fig.8. Parallel hybrid architecture combines two kinds of propulsion motors: electric motors and combustion engines which are mechanically coupled by the same shafts through gearboxes and clutches. The electrical motors and drive are supplied by electrical ESS and/or independent power sources (generators driven by combustion engines and/or Fuel Cell for example). The two propulsion systems can be used together or separately [20].

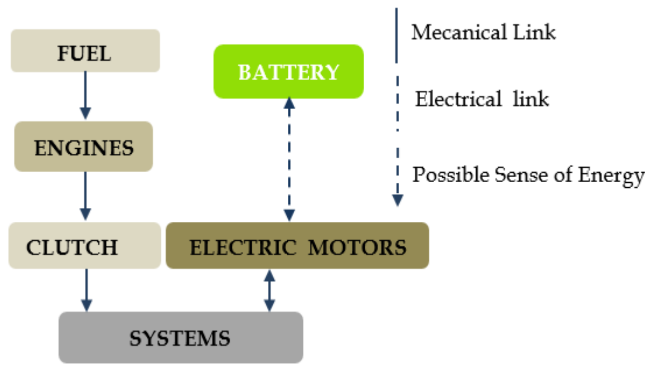


Fig. 8: Typical Parallel hybrid architecture (典型并联混合推进系统) [19]

Table 3: performances comparison of hybrid architectures topologies (混合推进系统的比较) [16, 18, 20, 22]

	Series HPS	Parallel HPS
Sizing of elements/costs	- To be fully efficient, the system must combine several power sources with rated power equal to a fraction of the total power. It leads to supplementary costs volumes and weight. - Electric propulsion motors sizing corresponds to the peak power.	- The sizing of each element of the propulsion systems is optimized. - Electrical motor sizing is reduced. - Supplementary costs and volume related to complex mechanical systems (clutches, gearboxes)

Power and Efficiency	- The efficiency is limited by the multiplication of systems in series (engine, generator, transformer, converters, motors, etc). - The system allows a precise control and gradual variation of the propeller speed. If several sources are used, combustion engines can be operated at their maximum efficiency.	- Good efficiency related to the reduced numbers of series components (particularly in combustion engine mode) - It allows precise control and a gradual variation of the propeller speed. - Combustion engine operates at peak efficiency.
Redundancy/reliability	The system is modular, and offers power sources redundancy	- Very high level of redundancy since because the propulsion power can be provided independently by two independent systems. - Complex mechanical system which can be a cause of failure.

In most cases one of the propulsion systems is devoted to low speed operations (classically the electric system) and the other one (classically the combustion engine) is used for high speeds. The first system can also be used as a boost system to provide a supplementary power during transient (starting, acceleration, etc.). This architecture reduces the number of elements compared to the series hybridization and allows optimizing the sizing of each of the energy sources [21].
Table 3 gives a comparison between the series and parallel hybridization architectures, in terms of coasts, redundancy and efficiency.

- *Series-Parallel Hybrid architecture*

The series-parallel architecture combines both architectures defined previously. This association allows the switching from the parallel to the serial HPS [18, 22].

C. *Power sources in HPS*

This section presents the main power sources and energy storage systems which can be used in HSP. The minimization of the fuel consumption on operating cycle requires the knowledge of the behavior of these different energy sources.

1) *Unconventional Power generation systems*

Fuel cells can be an interesting alternative for power production on small ships with very low emissions. It is an electrochemical device that converts chemical energy of a fuel into electrical energy [23-25]. It has the life expectancy of a diesel engine.
Fuel cells are classified according to operating temperature and the nature of the used electrolyte. There are two categories of fuel cells: high-temperature and low-temperature fuel cell [25-26]. Low temperature fuel cell categories include the Alkaline Fuel Cells (AFC), the Proton Exchange Membrane Fuel Cells (PEMFC), the Direct Methanol Fuel Cells (DMFC) and the Phosphoric Acid Fuel Cells (PAFC). These Fuel Cells are characterized by an operating temperature from 50 to 250°C [18, 25, 27]. High temperature fuel cells include the Solid Oxid Fuel Cells (SOFC) and the Molten Carbonate Fuel Cells (MCFC). Their operating temperatures are comprised between 650 and 1000°C [23-25].

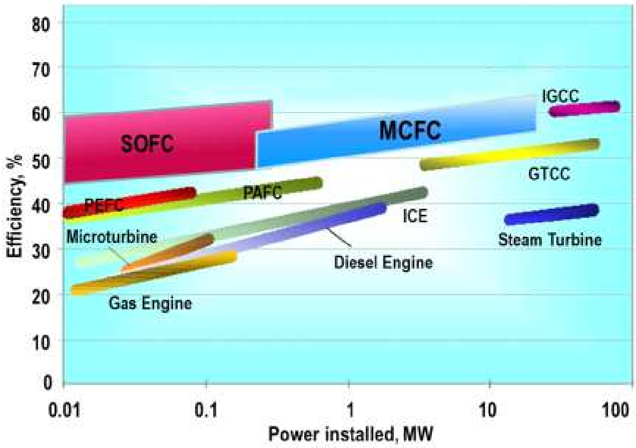


Fig.9: Comparison of the efficiency and electrical power installed for the combustion-based systems and fuel cell systems (内燃机系统及燃料电池系统的电力效能比较) [28]

The Fig.9 shows a comparison between the different elements of generation of energy, and shows that PEMFC have an efficiency up to 45% (efficiency of PSCF is about 40% and diesel engine efficiency is about 35%). It can provide high efficiency power with zero emission.
It can be also noticed that PEMFC technology is characterized by relatively low operating temperature which ensures an easy and quick start which could be interesting for vessels with a variable duty cycle [20, 28]. Another advantage is its significant lifetime compared to other fuel cells types. All this points indicate that PEMFC can be a very attractive element for HPS for low power small ship.

2) *Electric storage system*

An intermediate energy storage device can be used to better manage the energy and reduce the effects of peak power level on the sizing of the energy sources. The integration of energy storage systems offers interesting solutions for the efficiency and optimal use of energy. It can also lead to a significant reduction in noise and vibration compared to conventional systems [28].

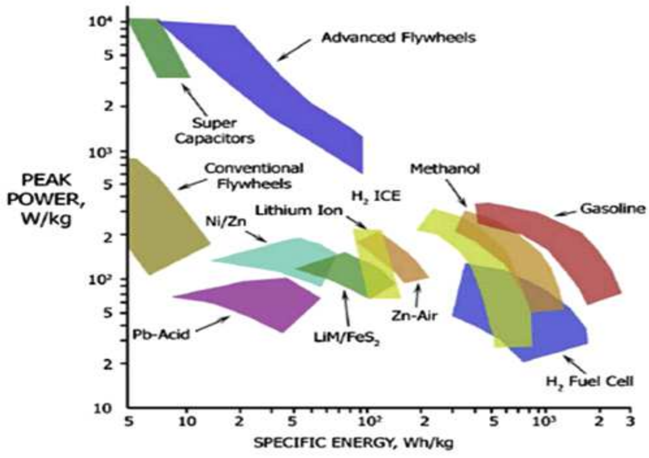


Fig.10: Ragone diagram of several storage systems (不同储能系统的应用范围图) [29]

Fig.10 gives a comparison of different energy storage systems in terms of specific energy and peak power.

Batteries are the most used systems. As shown in Fig. 10 lithium-ion batteries presents significant advantages compared to other battery types, particularly in term of energy density and efficiency [28]. However, like fuel cells, batteries are characterized by a low dynamic and thus cannot cope with transitional regimes.

Supercapacitors are interesting intermediate energy storage systems for small ships with short power transients. They are characterized by a high value of charge and discharge peak power and can be used to rapid dynamic storage with very low specific energy. They are usually associated with batteries and fuel cells, to manage high power short transients [28]. They can operate at very low temperatures at which many types of electrochemical batteries stop working.

Flywheels can also be used in some particular cases. Like supercapacitors, they are characterized by a high power density but a relatively low energy density. However using flywheels leads to implement safety systems to protect crew and passengers from possible flywheel failure. So their use in small ship context seems very limited.

D. Examples of electrical and hybrid vessels

1) Zempships "Alterwaser"

This vessel is the result of Zemships-EU project (Zero Emission Ships) [30, 31]. It has been launched in Hamburg in 2008 and it is one of the first boats developed using fuel cells. A picture of this boat is given in Fig. 11. Table 4 summarizes its specifications

Fig.11: Zempships Atlterwaser Boat (from http://www.proton-motor.com/zemships/) (Zemships 公司的 Atlerwaser 船，图片出自 from http://www.proton-motor.com/zemships/)

Table 4: Parameters of the Zempships Atlterwaser boat (Data from [30-31]) (Zemships 公司的 Atlerwaser 船舶参数，数据来自[30-31])

Parameters	Value
Motor peak power	120kW
PEM FC rated power	80kW
FC voltage	140-260V
FC current	280-520A
Battery (Lead Gel)	560V/360AH
Displacement of water	72t
Length	25.56 m
Width	5.20 m
Passenger capacity	100
Maximum speed	14km/h

This boat uses PEM FC as main power source and Lead Batteries as ESS as shown in Fig. 12 [23]. This hybrid system allows meeting the requirement of a short power cycle with high power transients as shown in Fig. 13.

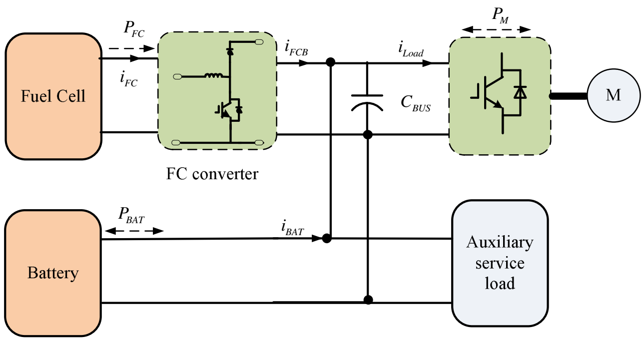


Fig.12: Energy/propulsion Architecture for Zempships Atlterwaser Boat from (Zemships 公司的 Atlerwaser 船舶电能推进系统) [23]

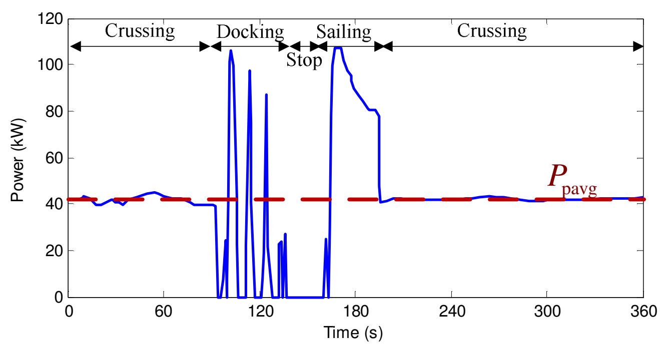


Fig. 13: Typical load cycle of Zempships Atlterwaser boat from [23] (Zemships 公司的 Atlerwaser 船舶的典型负载曲线)

2) Nemo H2

This project is quite similar to "Alterwaser" boat. The ship was launched in Amsterdam in 2009. Nemo H2 (shown in Fig. 14) is 22 meters in length and can carry 86 passengers. The propulsion is based on a series architecture where the power is supplied by a PEMFC (60-70kW) [22, 32]. When the ship is not at full power, batteries lead-acid (30-50kW) are charged. These batteries can then provide extra power when needed [32, 33].

Fig. 14: Nemo H2 Amsterdam [19]
(Nemo H2 游船，阿姆斯特丹)

3) Hybrid TUG RT Adrian [34]

A new generation of hybrid propulsion tug has been built in 2011. This first European hybrid tug, called RT Adrian (Fig.15) is used in the port of Rotterdam. The tug hybrid architecture, called “XeroPoint Hybrid Propulsion System’’ is a series/parallel hybrid architecture combining diesel engines, battery pack and diesel generators as shown in Fig.16. The propulsion system can be used in all-electric or diesel electric mode (for low power modes), conventional mode in the mid power range or in combined mode for full power. In this combined mode, diesel propulsion engines, and electrical motors are used simultaneously.

Fig. 15: Hybrid TUG RT Adrian in the port of Rotterdam [34]
(混合推进的 TUG RT Adrian 驳船，鹿特丹港口)

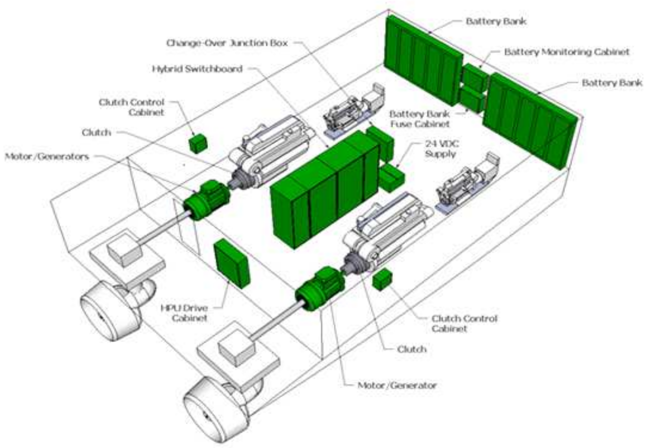


Fig. 16: Xeropoint Schematic propulsion system (source from [34])
(Xeropoint Schematic 船舶推进系统，来源于[34])

4) Bus electro-solar sea in La Rochelle (France)

This hybrid architecture boat can carry 75 passengers’ at a speed of 6 knots (Fig. 17). It is equipped with photovoltaic panels to assist the diesel engine to charge the batteries.

Fig. 17: Bus electro-solar sea in La Rochelle from [35]
(法国 La Rochelle 的太阳能电力客轮)

5) The ar Vag Tredan

This boat of 22.1 meters in length and 1.7 meters in draft, shown in Fig.18, has been built by the STX France shipyard in Lorient. Ar Vag Tredan is powered by supercapacitors used to provide power to two azimuth thrusters of 70kW. The ship can cruise at 10 knots during 2x7mn and ensure zero emissions operations. At each stop the 8 sets of 16 supercapacitors are recharged in 4 minutes [36].

Fig. 18: The ar Vag Tredan [36]
(法国 Ar Vag Tredan 超级电容客轮)

6) BatCub/Keolys project in Bordeaux (France)

BatCub project consists in using two catamaran shape water buses of 19 meters in length (Fig. 19). This particular hull shape allows increasing seakeeping. The energy/propulsion system is based on series hybrid propulsion (diesel-electric), which mainly operates on the electric mode. Each shuttle is equipped with a 140kWh lithium ion battery system [37]. The system powers two electric motors for propulsion and auxiliary systems such as lighting and communications. Coupled to diesel engine/generator, the battery is able to store the energy produced by the generator and provide

additional propulsive power when needed. Battery can be combined to diesel/generators during the boost phases,
During night, when the boat is docked, the batteries are charged by the harbor power grid. When they are fully charged the batteries can provide 6 hours of autonomy in all-electric operations.

Fig. 19: The BatCub/Keolys [38]
(法国布尔多的 BatCub Keolys 客船)

7) The Green Calanques (Marseille, France)

This tourist boat of 24 meters long by 6.7 meters wide, the "Green Calanques" (shown in Fig. 20) is able to sail at a speed of 20 knots in the Calanques (scenic steep-walled inlets) of Marseille in France. Callanques are touristic natural marine sites located in the south of France near the city of Marseille. To meet the requirements of low level emission which are related to these protected areas, this little ship is equipped with two Hélion fuel cells and two solar panels to recharge auxiliary batteries [39].

Fig. 20: The Green Calanques in Marseille's Callanques[40]
(法国马赛 Callanques 海湾的 Green Calanques 游船)

V. Conclusion

This paper shows that Electric and Hybrid Propulsion Systems are very interesting solution to optimize the behavior of small and low power ship in terms of efficiency and pollutant emissions.
After a brief description of the main challenges for the design of the energy/propulsion systems for small ships, hybrid architectures are presented, highlighting the key components. The study is supported by examples of small ships with hybrid and electric propulsion.

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