Fuel Cell Power Systems

Subjects: Energy & Fuels

Contributor: HUI XING

Fuel cells as clean power sources are very attractive for the maritime sector, which is committed to sustainability and reducing greenhouse gas and atmospheric pollutant emissions from ships.

maritime transportation | shipping emissions | fuel cells

1. Introduction

Marine diesel engines have driven the shipping industry for over a century. Owing to the use of fossil fuels and particularly marine residual oils, greenhouse gases (GHG) and air pollutants from ships, such as carbon dioxide (CO_2), nitrogen oxides (NO_x), sulfur oxides (SO_x) and particulate matters (PM), have become the key regulatory targets in the maritime sector [1]. The International Maritime Organization (IMO) has adopted a variety of regulations under Annex VI (titled Regulations for the Prevention of Air Pollution from Ships) of the International Convention for the Prevention of Pollution from Ships (MARPOL) [2][3][4]. As well as this, the phasing out of GHG emissions from ships as soon as possible in this century has been set as a target [5]. Correspondingly, a series of technological and operational measures have been employed to mitigate shipping emissions and improve ship energy efficiency [6][7]. However, current measures are not sufficient to make the shipping industry consistent with the global response to the threat of climate change [8]. Hence, alternative fuels and energy sources are expected to play a vital role as a synergistic solution for reductions of SO_x, NO_x, PM and CO_2 emissions. Apart from innovative technologies and systems for traditional engines, fuel cell power systems are proposed to be an important option to improve the use of alternative marine fuels. High energy efficiencies make fuel cells very attractive compared to marine combustion engines and gas turbines (GTs), though the power capacities of fuel cells cannot cover all maritime applications. However, the efficiencies and power capacities of fuel cells continue to be a focal point of research and development, leading to constant improvements that bring the technology closer to widespread adoption with every passing year.

Maritime fuel cells used onboard underwater vehicles can be traced back to the 1960s [9]. Possible applications of fuel cells onboard merchant ships include: low power demand main propulsion; auxiliary power for hybrid propulsion; electricity generation; and emergency power supply [10]. Several demonstration projects for fuel cell applications in the merchant marine sector have been carried out since 2000 [11].

2. Marine Applications of Fuel Cell Power Systems

2.1. Fuel Cells for Maritime Demonstrations

Fuel cells have been used for military submarines since the 1960s, but civil applications of the technology did not arise until this century. Up to now, a large number of research and demonstration projects have verified the viability of fuel cells for maritime applications. Some noticeable demonstration projects of marine fuel cells since 2000 are shown in Table 1. Reduced emissions, increased efficiency and quiet operation make fuel cells attractive for future low carbon shipping. In particular, PEMFC, including HT-PEMFC, as well as MCFC and SOFC, are the most promising types of marine fuel cells.

Table 1. Noticeable demonstration projects of marine fuel cell systems since 2000. [9][11][12][13].

Types	Vessel/Project	Capacity	Fuel	Types	Vessel/Project	Capacity	Fuel
AFC	Hydra	6.9 kW	Metal hydride	HT-PEMFC	Pa-X-ell MS Mariella	2 × 30 kW	Methanol
	Hydrocell Oy	30 kW	Metal hydride		RiverCell	250 kW	Methanol
PEMFC	Elding	10 kW	H_2		MF Vågen	12 kW	H_2
	ZemShip Alsterwasser	96 kW	H_2		RiverCell ELEKTRA	3 × 100 kW	H_2
	Nemo H_2	60 kW	H_2	MCFC	MC WAP	150/500 kW	Diesel
	Hornblower Hybrid	32 kW	H_2		FellowSHIP Viking Lady	320 kW	LNG
	Hydrogenesis	12 kW	H_2		US SSFC	625 kW	Diesel
	SF-BREEZE	120 kW	H_2	SOFC	METHAPU Undine	20 kW	Methanol
	Cobalt 233 Zet	50 kW	H_2		SchIBZMS Forester	100 kW	Diesel
	US SSFC	500 kW	Diesel		FELICITAS subproject 2	250 kW	LNG

2.2. Marine PEMFC Power Systems

The early applications of PEMFC power systems in the maritime sector include: A 12-m-long yacht with a maximum cruising range of 225 km at a speed of 8 knots, which utilized 6 kg of hydrogen stored in three storage tanks at a pressure of 300 bar, and was powered by four 1.2 kW PEMFC modules combined with nine lead-gel batteries, generating a total power output of up to 20 kW [14]; a canal boat using the hydrogen stored in a five-cylinder metal hydride storage system, powered by a 5 kW PEMFC module together with a lead-acid battery [15]; and a small boat with a maximum operating time of 10 h at a maximum speed of 7 knots, which utilized 5 kg of hydrogen onboard and was powered by an 8 kW PEMFC module [16][17]. However, the installed power of these applications is usually less than 10 kW [9][18].

2.2.1. FCS Alsterwasser

FCS Alsterwasser was the first passenger ship powered by hydrogen fuel cells with a maximum power up to 100 kW. Based on the Zemships project, a PEMFC power system was developed for FCS Alsterwasser, which was about 25 m long and designed to accommodate up to 100 passengers at a maximum speed of 8 knots [19]. The power system consisted of twelve storage tanks with 50 kg of hydrogen at a pressure of 350 bar, two 48 kW PEMFC modules, 7 lead-gel battery packs with total capacities of 234 kWh and total voltage of 560 V, a 100 kW propulsion electric motor and a 20 kW bow thruster. The PEMFC power system was used to power the propulsion motor directly or charge the lead-gel battery packs. The battery packs, used as a back-up option if the fuel cells failed, not only delivered power to the propulsion motor at peak load but also lightened the load on the fuel cells during docking and casting-off procedures, which prolonged the life cycle of the fuel cells. The operation of the battery packs was determined by an energy management system. The hydrogen stored onboard allowed the ship to operate for 2–3 days without refueling, while it took only 12 min to fill up the hydrogen storage tanks.

2.2.2. Nemo H_2

A PEMFC power system was developed for Nemo H_2, which was about 22 m long and designed to accommodate about 88 passengers at a maximum speed of 8.6 knots [20]. The power system consisted of six storage tanks with 24 kg of hydrogen at a pressure of 350 bar, two 30 kW PEMFC modules, 55 lead-acid battery packs with total capacities of 70 kWh, a 75 kW propulsion electric motor and a 11 kW bow thruster. The PEMFC power system was used to power the propulsion motor directly or charge the lead-acid battery packs. The battery packs were used as a back-up option and to improve the performance of the fuel cells as well. An energy management system was used to determine the operation of the battery packs. The refueling process happened once a day.

2.2.3. SF-BREEZE

SF-BREEZE was a concept hydrogen-powered passenger ferry, which was developed to accommodate 150 passengers at a maximum speed of 35 knots [21]. The power system consisted of a single Type C (pressurized vessel) storage tank on the top deck with 1200 kg of LH_2, 41 120 kW PEMFC modules containing four 30 kW PEMFC stacks each, DC-DC converters, DC-AC inverters and two waterjet propulsion systems driven by AC motors with a power of 2000 kW each. In addition, 120 kW of power was used for auxiliary systems such as HVAC and 400 kW was retained for a working margin. No additional battery packs were installed and the endurance was up to 100 nautical miles before refueling. The shoreside refueling facility needed to be able to provide fuel to the vessel twice a day.

2.2.4. A Tourist Boat

A PEMFC power system was developed for a 20-m-long tourist boat, which had a light weight of 20 tons and accommodated a maximum of 50 passengers [18]. Fuel storage consisted of fourteen storage tanks with 74 L hydrogen each at 350 bar, resulting in a total hydrogen capacity of 25 kg onboard. The power system consisted of two 28 kW PEMFC modules, two 25 kW DC-DC converters with input voltages of 82–170 V and output voltages of 240–370 V, three 15.7 kWh Li-ion battery packs, a battery charger and a waterjet propulsion system with a maximum power of 86 kW. The total volume of the system was 7.41 m^3 and the total weight was 2190 kg, where the storage tanks including hydrogen were 4.25 m^3 and 712 kg respectively. The hydrogen stored onboard allowed the PEMFC modules to operate at the maximum power output of 50 kW for about 8 h. When the boat was propelled by the PEMFC modules only, the speed of the boat was 4.5–5.6 knots at power outputs of 38–51 kW. However, when the PEMFC modules and the Li-ion battery packs delivered power to the boat together, the speed reached 6.6–7.8 knots at a total power output of about 85 kW. For a higher speed, the PEMFC power system would need to be several times the volume and weight of installed version. Therefore, there were some technical and economic limitations for the widespread maritime application of PEMFC power systems due to the relatively low power densities of PEMFCs and the low volumetric energy density of hydrogen storage systems.

2.2.5. Others

Based on the E4Ships Pa-X-ell project, a 60 kW modularized HT-PEMFC power system fueled by methanol was developed for the auxiliary power supply onboard the passenger ship MS Mariella [22][23]. The power system included two 30 kW HT-PEMFC units, each of which comprised six 5 kW modules. The fuel cell stack, the reformer, the afterburner, the in-process heat exchanger, the DC-DC converter and the control units were integrated in one module housing with an exhaust as well as fuel and cooling water piping. In addition, a methanol tank was installed.

Based on the RiverCell project [11], a 250 kW modularized HT-PEMFC power system fueled by methanol was developed as a part of a hybrid power supply for river cruise vessels. Meanwhile, the feasibility of a 192 kW HT-PEMFC power system fueled by hydrogen combining with 1250 kWh fully charged battery packs was conducted. The ship had six storage tanks with 740 kg of hydrogen at a pressure of under 500 bar.

Compared to PEMFC power systems, HT-PEMFC power systems improved the fuel flexibility and avoided complex water management. WHR was also possible with the HT-PEMFC system.

In addition, a hybrid power system was developed to provide the main and auxiliary power of a cruise ship in Stockholm [24]. Solar PV, PEMFC and diesel generators were taken as power sources, and a DC-bus, an AC-bus and a DC-AC inverter were used to collect, distribute and convert power. However, the energy production from the PEMFC was extremely low since the hydrogen production for the PEMFC mainly depended on the surplus electrical power from the solar PV.

2.3. Marine MCFC Power Systems

The offshore supply vessel Viking Lady, which utilized fully electric propulsion powered by dual fuel engines, was the first ship using a MCFC power system onboard as an APU [25]. The newly installed MCFC and existing power plant used the same LNG fuel and supply system. The 320 kW MCFC module was newly developed and comprised of a stack of 500 fuel cells, as well as an internal reforming unit and a WHR system. The MCFC module delivered a DC voltage varying between 380–520 V depending on its load condition and age (expected operational lifetime of 24,000 h). The electrical system had been designed to compensate for the slow response of the fuel cells in order to keep stable conditions to protect against harmful dynamic load changes which could diminish the lifetime of the fuel cells. When the FellowSHIP project entered into the third phase, marine lithium ion battery packs were integrated into the ship power system. When the ship operated at low loads, such as maneuvering or berthing, the fuel cells and its batteries operated alone and relieved the concern of methane slip from the LNG-fueled engines, which would reduce emissions, noise and vibrations significantly.

Apart from the Viking Lady, a 28 MW MCFC-based propulsion system, which consumed both LNG and hydrogen boil-off gas as fuel, was developed for a 140,000 m^3 LH_2 tanker [26][27][28]. In addition, a 625 kW MCFC power system and a 500 kW (concept design)/150 kW (final design) MCFC power system were developed based on the US SSFC project and the MC-WAP project, respectively [11], both of which were fueled by diesel; no application demonstrations were carried out onboard ships.

2.4. Marine SOFC Power Systems

Based on the METAPHU project, the conceptual study of a 250 kW SOFC APU using methanol was finished, and practical operation of a 20 kW SOFC unit onboard car carrier MV Undine has been carried out [29]. This 20 kW SOFC unit, which was independent of the ship's propulsion source or main electric system, just aimed at testing the performance and emissions under real-life conditions onboard a ship and at assessing the maturity of methanol-based technology in the shipping sector. The SOFC system comprised a methanol tank, a reformer, the SOFC stack, a catalytic combustion afterburner and in-process heat exchangers [30][31]. The SOFC stack ran on hydrogen and the methanol (or NG in other SOFC applications) was reformed prior to entering the stack. Part of the anode gas was recirculated for methanol reforming and another part was burned with the cathode exit gas in a catalytic burner. The stack operated at the temperature of 600–900 °C. The air was preheated by the cathode exit gas through a heat exchanger. The heat of the exhaust gas from the catalytic burner was absorbed by the methanol prior to entering the reformer through a heat exchanger and was further absorbed by an economizer.

Based on E4Ships SchIBZ project, a hybrid power system combining a 50 kW containerized SOFC unit with lithium-ion battery packs was developed for the auxiliary power supply onboard the general cargo ship MS Forester [23]. The hybrid power system comprised a diesel tank, a water tank, a reformer, the SOFC stack, a catalytic combustion afterburner operating at a temperature of 750 °C, a heat exchanger for WHR, lithium-ion battery packs to compensate the fluctuations of the electrical loads and power electronics. The SOFC module fueled by low-sulphur diesel (maximum 15 ppm sulphur) was expected to provide 25–50% of the onboard power demand. In addition, the power output of the SOFC stack could be scalable up to 500 kW. The module operated at a temperature of around 800 °C, and the heat recovery of exhaust gases and the integrated reforming process made it possible to achieve a higher overall efficiency [11].

References

1. IMO. Third IMO GHG Study 2014; Technical Report; International Maritime Organization: London, UK, 2015.
2. IMO. Amendments to the Annex of the Protocol of 1997 to Amend the International Convention for the Prevention of Pollution from Ships, 1973, as Modified by the Protocol of 1978 Relating Thereto; Resolution MEPC.203(62); IMO: London, UK, 15 July 2011.
3. IMO. 2012 Guidelines on the Method of Calculation of the Attained Energy Efficiency Design Index (EEDI) for New Ships; Resolution MEPC.212(63); IMO: London, UK, 2 March 2012.
4. IMO. 2012 Guidelines for the Development of a Ship Energy Efficiency Management Plan (SEEMP); Resolution MEPC.213(63); IMO: London, UK, 2 March 2012.
5. IMO. Initial IMO Strategy on Reduction of GHG Emissions from Ships; Resolution MEPC.304(72); IMO: London, UK, 13 April 2018.
6. Bouman, E.A.; Lindstad, E.; Rialland, A.I.; Strømman, A.H. State-of-the-art technologies, measures, and potential for reducing GHG emissions from shipping—A review. Transport. Res. Part D Transport. Environ. 2017, 52, 408–421.
7. Xing, H.; Spence, S.; Chen, H. A comprehensive review on countermeasures for CO2 emissions from ships. Renew. Sustain. Energy Rev. 2020, 134, 110222.
8. CE Delft; UMAS. Study on Methods and Considerations for the Determination of Greenhouse Gas Emission Reduction for International Shipping; Final Report Prepared for the European Commission; European Commission: Brussels, Belgium, 2019.
9. McConnell, V.P. Now, voyager? The increasing marine use of fuel cells. Fuel Cells Bull. 2010, 2010, 12–17.
10. Sattler, G. Fuel cells going on-board. J. Power Sources 2000, 86, 61–67.
11. Tronstad, T.; Åstrand, H.H.; Haugom, G.P.; Langfeldt, L. Study on the Use of Fuel cells in Shipping; Report to European Maritime Safety Agency by DNV GL; DNV GL: Oslo, Norway, 2017.
12. Van Biert, L.; Godjevac, M.; Visser, K.; Aravind, P.V. A review of fuel cell systems for maritime applications. J. Power Sources 2016, 327, 345–364.
13. Markowski, J.; Pielecha, I. The potential of fuel cells as a drive source of maritime transport. IOP Conf. Ser. Earth Environ. Sci. 2019, 214, 012019.

14. MTU Friedrichshafen GmbH. First yacht with certified fuel cell propulsion. Fuel Cells Bull. 2003, 2003, 4–5.
15. Green Car Congress. Hydrogen Hybrid Canal Boat. 24 September 2007. Available online: https://www.greencarcongress.com/2007/09/hydrogen-hybrid.html (accessed on 24 June 2020).
16. Hydrogenics Corporation. Turkish fuel cell boat powered, refuelled by Hydrogenics tech. Fuel Cells Bull. 2012, 2012, 2–3.
17. Yazici, M.S.; Hatipoglu, M. Hydrogen and fuel cell demonstration in Turkey. Energy Procedia 2012, 29, 683–689.
18. Choi, C.H.; Yu, S.; Han, I.-S.; Kho, B.-K.; Kang, D.-G.; Lee, H.Y.; Seo, M.-S.; Kong, J.-W.; Kim, G.; Ahn, J.-W.; et al. Development and demonstration of PEM fuel-cell-battery hybrid system for propulsion of tourist boat. Int. J. Hydrogen Energy 2016, 41, 3591–3599.
19. Zemships. One Hundred Passengers and Zero Emissions: The First Ever Passenger Vessel to Sail Propelled by Fuel Cells. Available online: https://ec.europa.eu/environment/life/project/Projects/index.cfm?fuseaction=home.showFile&rep=file&fil=Zemships_Brochure_EN.pdf (accessed on 24 June 2020).
20. Chakraborty, S.; Dzielendziak, A.S.; Köroğlu, T.; Yang, K. Evaluation of Smart Eco-Friendly Public Transport Options in Coastal Cities: Towards a Green Future for the City of Southampton; LRF Collegium 2013 Series; University of Southampton: Southampton, UK, 2013; Volume 2.
21. Pratt, J.W.; Klebanoff, L.E. Feasibility of the SF-BREEZE: A Zero-Emission, Hydrogen Fuel Cell, High-Speed Passenger Ferry; SANDIA Report; SAND2016-9719; Sandia National Laboratories: Livermore, CA, USA, 2016.
22. German e4ships project reports on fuel cell maritime demos. Fuel Cells Bull. 2016, 2016, 5, 11.
23. E4ships. Fuel Cells in Marine Applications (2009–2016). December 2016. Available online: https://www.e4ships.de/english/news/ (accessed on 24 June 2020).
24. Ghenai, C.; Bettayeb, M.; Brdjanin, B.; Hamid, A.K. Hybrid solar PV/PEM fuel cell/diesel generator power system for cruise ship: A case study in Stockholm, Sweden. Case Stud. Therm. Eng. 2019, 14, 100497.
25. Ovrum, E.; Dimopoulos, G. A validated dynamic model of the first marine molten carbonate fuel cell. Appl. Therm. Eng. 2012, 35, 15–28.
26. Ahn, J.; Noh, Y.; Park, S.H.; Choi, B.I.; Chang, D. Fuzzy-based failure mode and effect analysis (FMEA) of a hybrid molten carbonate fuel cell (MCFC) and gas turbine system for marine propulsion. J. Power Sources 2017, 364, 226–233.

27. Ahn, J.; Park, S.H.; Lee, S.; Noh, Y.; Chang, D. Molten carbonate fuel cell (MCFC)-based hybrid propulsion systems for a liquefied hydrogen tanker. Int. J. Hydrogen Energy 2018, 43, 7525–7537.
28. Ahn, J.; You, H.; Ryu, J.; Chang, D. Strategy for selecting an optimal propulsion system of a liquefied hydrogen tanker. Int. J. Hydrogen Energy 2017, 42, 5366–5380.
29. METHAPU prototypes methanol SOFC for ships. Fuel Cells Bull. 2008, 2008, 4–5.
30. Green Car Congress. Project to Start Trials on Ship-Board Methanol SOFC APU. 18 March 2008. Available online: https://www.greencarcongress.com/2008/03/project-to-star.html (accessed on 24 June 2020).
31. Strazza, C.; Borghi, A.D.; Costamagna, P.; Traverso, A.; Santin, M. Comparative LCA of methanol-fuelled SOFCs as auxiliary power systems on-board ships. Appl. Energy 2010, 87, 1670–1678.