A review of fuel cell systems for maritime applications

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Abstract*:* Progressing limits on pollutant emissions oblige ship owners to reduce the environmental impact of their operating vessels. Fuel cells may provide a suitable solution, since they are fuel efficient as they emit few hazardous compounds. Various choices can be made with regard to the type of fuel cell system and logistic fuel, and it is unclear which have the best prospects for maritime application. An overview of fuel cell types and fuel processing equipment is presented, and maritime fuel cell application is reviewed with regard to efficiency, gravimetric and volumetric density, dynamic behaviour, environmental impact, safety and economics. It is shown that low temperature fuel cells using liquefied hydrogen provide a compact solution for ships with a refuelling interval up to a ten of hours, but may result in total system sizes up to five times larger than high temperature fuel cells and more energy dense fuels for vessels with longer mission requirements. The expanding infrastructure of liquefied natural gas and development state of natural gas-fuelled fuel cell systems can facilitate the introduction of gaseous fuels and fuel cells on ships. Fuel cell combined cycles, hybridisation with auxiliary electricity storage systems and redundancy improvements are identified as topics for further study.

*Index Terms***— Fuel cells, Logistic fuels, Fuel processing, Ships Maritime application, Emissions.**

I. INTRODUCTION

Technology improvements in recent decades have reduced the fuel consumption and environmental impact of ships. However, shipping remains a significant contributor to global emissions of greenhouse gases (GHGs), volatile organic compounds (VOCs), particulate matter (PM), hazardous air pollutants, NOX and SOX. It is estimated that shipping activities contribute to 3 to 5% of global carbon dioxide (CO2) emissions and over 5% of global SOX emissions. State of the art propulsion technology in shipping has not kept pace with road transport for various reasons, the most important being the absence of strict regulations on environmental impact at sea.

With cost of ownership being the main technology driver, economical but polluting diesel engines and cheap heavy fuels have become default choices for maritime power generation. Recently announced regulations are, however, set to change the common practice in maritime power generation. Although eventually postponed to 2021, the international maritime organization (IMO) recently adopted stringent emission limits in its Tier III regulation, most notably on NOX and SOX emissions. For emission control areas (ECAs) these requirements are particularly strict and will be difficult to meet with traditional diesel engines and bunker fuels.

Ship owners need to adopt solutions to bring exhaust emissions within these and other future limits. These include: engine improvements, such as exhaust gas recirculation, two stage turbocharging, late miller timing, smart combustion chamber design and advanced fuel injection systems; exhaust gas after treatment, like scrubbers or selective catalytic reduction; and finally the use of different bunker fuels, for example low sulphur diesel or liquefied natural gas (LNG). A combination of these methods will be required, and this is likely to increase size, complexity, fuel consumption and maintenance of maritime power plants.

Fuel cell systems differ substantially from each other, and it is not clear which system has the best future prospects. An overview of fuel cell systems is provided in this review. Then, various fuel cell systems are evaluated according to important performance criteria for maritime application: fuel consumption, power and energy density, load-following capabilities and environmental impact.

Finally, safety and economics are briefly discussed followed by case studies of the related projects.

II. FUEL CELL SYSTEMS FOR SHIPS

Electrical power in ships is mainly used for auxiliaries, although there is a tendency towards the use of electricity for propulsion as well. For example in hybrid configurations, and in the all-electric ship concept, where advanced electrical propulsion techniques and electrical storage components can be used.

A vast majority of ships currently uses diesel generators to produce electricity, where chemical energy is converted into electricity via thermal and mechanical energy. In contrast, fuel cells convert chemical energy directly into electrical energy, thus omitting the indirect route via thermal energy in combustion engines.

III. ENVIRONMENTAL IMPACT

The potential reduction of local emissions during operation is an important incentive to apply fuel cell systems in ships, since these are typically subject of environmental regulations. For example, Ludvigsen et al.discuss the possibility to eliminate local hazardous emissions completely and reduce local GHG emissions significantly. No SOX, low NOX and 40% reduced CO2 emissions were demonstrated with a 20 kW MeOH-fuelled maritime SOFC system in the METHAPU project.

Gas engines have significantly lower emissions of NOX and PM compared to diesel engines, but fuel slip results in much higher emissions of VOCs, mostly methane, and CO. Fuel cell systems have virtually zero emissions of NOX, PM, VOCs and CO, and the higher electrical efficiency results in reduced CO2 emissions.

Although the potential of fuel cells to reduce local emissions during their operational life, it represents only a part of the environmental impact over a complete life cycle. Next to the impact during the operational life, the complete environmental burden from maritime electricity generators is determined by contributions from:

_ Manufacturing;
_ Maintenance;
_ Decommissioning;
_ Fuel supply.

Manufacturing, maintenance and decommissioning stages may be important since the energy intensive production processes and limited lifetimes of fuel cell systems can result in a net increase in environmental impact. Fuel supply considerations account for the production, processing and transportation of fuels. For example, although shows reduced tank-to-electricity CO2 emissions for LNG compared to MGO, it has been argued that methane emissions associated with its production and distribution may in some cases result in a net increase in GHG impact.

In contrast to the manufacturing, maintenance and decommissioning stages, fuel supply considerations are only partly fuel cell specific. Stringent fuel quality requirements may impose additional fuel processing, and the supplied fuel may influence the performance of the fuel cell system. Other aspects of fuel supply, such as origin and transport, are similar for fuel cell systems and combustion engines and are, therefore, out of the scope of this review. However, it should be noted that these aspects have an important contribution to the environmental impact of maritime electricity generation.

Three life cycle assessments have been carried out for maritime fuel cell systems. Two of them assume continued use of diesel fuels for the traditional engine-generator sets, while renewables are considered only for the fuel cell system. However, a complete life cycle assessment should evaluate the use of renewable fuels in conventional generators as well. Pehnt shows, for example, that using renewable hydrogen in an internal combustion engine may still result in lower GHG emissions compared to a fuel cell based drivetrain over a complete life cycle, although others argue differently.

Altmann et al. analyse the life cycle performance of diesel engines, fuelled with heavy fuel oils, as well as high temperature fuel cells using low sulphur diesel fuels or LNG and low temperature PEMFCs on hydrogen from various sources. Emissions of hazardous pollutants are found to be much lower for fuel cell systems.

Although different fuelling options are considered for the investigated systems, various hydrogen origins are analysed for the PEMFC system, showing that reduced GHG emissions are only achieved if the hydrogen is produced from a renewable source.

In a study by Strazza et al. a traditional diesel-generator set is compared to a maritime SOFC system. Rather than frequent stack replacement, maintenance after every 6000 operating hours is assumed to be sufficient. Similar to the study of Altmann et al, several fuelling options are analysed for the SOFC system, while only diesel fuel is considered for the internal combustion engine. The results show that the environmental impact of SOFC operation and manufacturing is low compared to the fuel extraction and refining phase.

Alkaner et al. compare a conventional diesel-generator to a diesel-fuelled MCFC system. They conclude that the net environmental impact of the MCFC system is lower, mainly due to reduced emissions during its operational life. However, the manufacturing phase of the MCFC is responsible for a significantly higher environmental impact than that of the diesel-generator. This is partly due to necessary stack replacement every 5 years. Maintenance requirements for the diesel generator are neglected in this study.

Similar assessments have been carried out for non-maritime applications. An SOFC auxiliary power unit fuelled with diesel is compared to electricity generation with an idling truck diesel engine in a study by Baratto et al. Clear advantages in environmental impact for the fuel cell unit are reported, partly because idling diesel engines operate far from their optimal operational conditions. Although this comparison is not representative for heavy duty diesel-generator sets, it demonstrates the potential to reduce the environmental impact of ships in low load conditions.

Fuel cell generators can offer an alternative for so-called cold ironing, where ships are connected to the land-based electricity grid during berth. Pratt et al. analysed a conceptual barge mounted hydrogen fuelled PEMFC system for cold ironing purposes, concluding that such a system could be both technically and commercially feasible.

General aspects of life cycle assessments of fuel cell systems are discussed by Pehnt. A detailed analysis of both low and high temperature fuel cells is presented, for mobile applications as well as stationary power generation, and several important uncertainties are pointed out. For example, fuel cell production methods vary and are still likely to change, and the possibility of recycling is often unknown. The study concludes that high temperature fuel cell systems have clear environmental benefits over conventional generators during a complete life cycle, due to fuel savings and emission reductions during their operational life. Low temperature fuel cells have this potential if renewable hydrogen is available, for example generated via electrolysis.

IV. SAFETIES AND AVAILABILITY

Like every power plant for maritime applications, fuel cell systems will have to comply with classification standards. These regulations usually differ from land-based systems, and make sure that a vessel can be operated safely and reliably. For example, single point failures should be avoided, since complete loss of power due to an emergency shutdown is not desirable. It is expected that a redundant fuel cell system design, equipped with adequate ventilation, fire suppression, monitoring and control systems, will meet all classification requirements.

Fuel cell systems have few mechanical parts and tend to degrade rather than fail, which results in a high availability. This is further enhanced by the modularity of fuel cell systems, which allows clean, silent and reliable distributed electricity production next to large consumers. This increases the redundancy of the electricity grid, and is one of the reasons some companies have, although yet modest, commercial success applying fuel cell systems in data centers and backup power generation for telecom systems. Next to the fuel cell system itself, classification rules on logistic fuels are of particular importance. Fuels that are either harmful, hazardous or have a flash points below 60_ C, will need special precautions before their use on-board will be allowed. Some fuels, such as ammonia and MeOH, are toxic to humans and animals, while other alternatives, such as hydrogen and DME have the advantage that they are non-toxic, non-mutagenic and noncarcinogenic. It should be noted that conventional diesel oils are toxic as well. Volatile, low flashpoint fuels, such as hydrogen and NG, impose the risk of explosions in closed spaces. These fuels will have to comply with the two-barrier-principle for gas supply, which is either achieved by double-walled piping, ventilation ducts or gas tight enclosures. This may be necessary as well for outlet piping, as these can still contain traces of hydrogen and CO. These issues are addressed by the recently approved International Code of Safety for Ships using Gases or other Low-flashpoint Fuels (IGF Code), although this code initially focusses on LNG and its applicability is restricted to vessels under the International Convention for the Safety of Life at Sea (SOLAS).

There is some awareness of these issues among fuel cell developers and classification societies, which is reflected in two recent publications. In particular the publication by Vogler et al. addresses several issues regarding gas safety, such as venting, explosion protection and high pressure storage. Ludvigsen et al. shortly discusses two different class notations for maritime fuel cell systems, FC-SAFETY and FC-POWER, both developed by DNV. However, current standards by classification bodies are based on limited experience with a small number of systems. Communication between system designers and classification societies should result in safe, yet not overly stringent rules for future fuel cell applications. In addition, the possibility to improve the redundancy and reliability of the electricity grid should be studied further.

V. ECONOMICS

The development of naval fuel cell systems commenced by the 1970s, and the first demonstration projects of the technology followed in the next two decades. Still, fuel cell systems have no substantial market share, and high costs are often mentioned as the main reason. PAFCs and MCFCs currently have the most advanced development state, and so far several MWs have been installed for stationary power. Despite this, capital investment cost is reported to be over 5000 $/kW for both system types. The HT-PEMFC, is anticipated to be more efficient and less expensive than the PAFC, although both fuel cell types still struggle with a limited lifetime.

Fuel cell systems in their current development state are significantly more expensive than conventional generators, but many companies see potential to reduce the cost of fuel cell technology.

Especially the LT-PEMFCs for the automotive sector have seen major price cuts in recent years. Although stack prices at the current production volume, 500 to 1000 midsized fuel cell vehicles per year, are typically still >1000$/kW, projected production costs for automotive LT-PEMFC stacks vary from 280 $/kW at an annual production volume of 20,000 units to 50 $/kW for 500,000 units. A price level of 50 $/kW would put them in direct competition with diesel generators, although lifetime issues and the high cost of the BoP, in particular if hydrocarbon fuels are used, still remain important issues.

Although the expected price level of high temperature fuel cell systems is higher, the reduced consumption of hydrocarbon fuels might provide a decent return on investment for these systems. The need for expensive platinum is omitted in high temperature fuel cells, but their active layers rely on rare earth oxides. Although these are far cheaper than platinum, a substantially larger amount is needed. In addition, the high operational temperature limits the material choices for other stack components, the specific power is usually lower and manufacturing costs are relatively high.

Lee et al. conclude from a study of stand-alone NG-fuelled SOFC systems that, in order to make such systems economically viable, there is a need to bring down the capital costs of the stack and the inverter, even if this would result in a lower system efficiency. The limited lifetime of the stack has an important effect on the results. Most studies assume a system life cycle of 20 to 30 years, whereas stack lifetime is currently 2 to 3 years. Although some manufacturers aspire lifetimes in the range of 5 to 7 years, this is still an ambitious target for most suppliers.

Although fuel cell systems already provide an economically attractive choice in specific business cases, such as material handling and back-up power, it is often stated that they will be economically attractive for a wider range of applications if a substantial market volume is attained. However, a recent study of domestic fuel cell systems by Staffel et al. shows that full market penetration may be required to achieve target prices at the current learning rates. This would imply that the fuel cell market will depend on government support programs for several decades, which leads to the conclusion that incremental learning should not be the only route to cost reduction.

While several car manufacturers are scaling up their LT-PEMFC production volume, researchers have taken SOFCs back to the laboratory to develop more cost effective fuel cell concepts before scaling up. Although it is difficult to estimate just how effective these efforts will be, some promising results have been published. Researchers in the SECA program claim that stack production costs of 175 $/kW can be achieved with current technology. In general, estimates of mass produced SOFC stack production cost vary from 150 to 1500 $/kW. This would be a competitive price level, provided that the cost of the BoP is lowered accordingly.

VI. CASE STUDIES

6.1. Class 212 submarines

The first preliminary studies of PEMFC based AIP systems for submarines started in the 1970s. This resulted in the development of such a system in the early 1980s, and finally the production of the Class 212 submarines by Howaldtswerke-Deutsche Werft (HDW) in 1998. The Siemens fuel cell system consists of two 120 kW PEMFC modules, hydrogen is stored in metal hydrides, and liquid oxygen is carried in a vacuum-insulated tank. Over thirty submarines with a fuel cell AIP system have been commissioned so far.

6.2. SSFC

The ship service fuel cell (SSFC) project started in 1997 and aimed to develop diesel-fuelled fuel cell systems for naval ships and other vessels. The goals were to reduce fuel consumption, noise, thermal signatures, maintenance cost and emissions. In addition, the distribution of generators throughout the ship should enhance survivability.

Conceptual designs for a 2.5 MW MCFC and PEMFC system were developed, and demonstrators of 0.5MWwere tested. High complexity, long start-up times and prices were pointed out as the most important issues.

6.3. DESIRE

The diesel reforming with fuel cell (DESIRE) project commenced in 2001 and developed a 25 kW technology demonstrator of a diesel fuel processor for PEMFCs, to be used for naval application. A small fuel cell system was successfully connected to the fuel processor.

Promising results were presented, but problems with sulphur removal, load transients and robustness were identified.

6.4. FCSHIP

In the fuel cell technology for ships (FCSHIP) project a large consortium of European partners cooperated in providing a roadmap for future research and development on waterborne fuel cell application. Operational and safety requirements were investigated, and conceptual designs were developed. Finally, the life cycle impact of a marinised MCFC system was assessed and compared to a conventional diesel engine-generator set.

6.5. FellowSHIP

A 330 kW LNG-fuelled MCFC was installed on-board of the offshore supply vessel 'Viking Lady' in the fuel cells for low emissions ships (FellowSHIP) project. The fuel cell system was operated successfully for 18,500 h, and demonstrated a net electrical efficiency of ~44.4% with no detectable NOX, SOX and PM emissions.

6.6. FELICITAS

The fuel cell power trains and clustering in heavy-duty transport (FELICITAS) project studied multiple heavy duty power trains, among which a SOFC auxiliary power unit for a mega yacht. Various marinisation aspects of SOFC technology where investigated, as well as hybridisation with flywheels. Furthermore, coupling of the SOFC systems with a gas turbine and the heating ventilation and air-conditioning system was examined.

6.7. MC-WAP

The objective of the 2005 molten-carbonate fuel cells for waterborne application (MC-WAP) project was to develop and test a 0.5 MW MCFC auxiliary power generators for on-board testing on RoPax, RoRo and cruise vessels. Eventually tests were performed on an existing MCFC research plant and various conceptual designs were developed.

6.8. ZEMSHIP

The passenger vessel FCS Alsterwasser was equipped with a hydrogen-fuelled PEMFC system in the zero emission ship (ZEMSHIP) project, and was operated successfully for two seasons. The vessel was heavily damaged in a fire during a test run, caused by overheating of the lead-acid batteries. Since the fuel cell system and the hydrogen storage were not damaged, the incident proved the suitability of the applied hydrogen safety concept.

6.9. METHAPU

In the methanol auxiliary power unit (METHAPU) project a 20 kW SOFC demonstrator was marinised and tested on-board of the car carrier 'Undine'. Additional objectives of the project were to facilitate the introduction of international regulations on MeOH as a marine fuel, and to assess the environmental impact of such applications.

6.10. Nemo H2

Fuel Cell Boat BV has developed the passenger vessel Nemo H2 for canal cruises in Amsterdam. It is propelled with a 60 to 70 kW

PEMFC system, hybridised with a 55 kW lead acid battery pack. The vessel was delivered in 2011, but has not entered active service as of now due to the absence of a permanent hydrogen fuelling station.

6.11. SchIBZ

The ship-integrated fuel cell (SchIBZ) project started in 2009 and is still ongoing. The target of the project is to install and evaluate a 0.5 MW diesel-reformer integrated SOFC system on the vessel 'MS Forester'. Design calculations showed that LHV efficiency up to 55% can be obtained. So far, a 27 kW system demonstrated an electrical efficiency over 50% on low sulphur diesel for more than 1000 h.

Tests with a 50 kWsystem at sea are planned for 2016.

6.12. Pa-X-ell

The Pa-X-ell project is part of the same program as the SchIBZ project. The Pa-X-ll project focusses on the integration and safety aspects of MeOH-fuelled HT-PEMFC systems in cruise ships. Investigations include the placement of fuel cells in different fire zones, safe supply of low-flashpoint fuels, and thermal and electrical integration of fuel cells. A 120 kW fuel cell container has been developed for long term trials.

VII. SUMMARY

This review provided a resume of fuel cell types, logistic fuels and fuel processing equipment, to provide insight into the implications of choices for fuel cell types and logistic fuels on the overall fuel cell system characterises. This supported an analysis of the

suitability of these systems for electrical power generating on-board ships, for which electrical efficiency, gravimetric and volumetric density, system dynamics, environmental impact, safety and economics were discussed. Finally an overview of research projects on maritime fuel cell application was presented.

Low temperature fuel cells can achieve high electrical efficiencies if hydrogen is available as a logistic fuel. However, the efficiency is significantly reduced if hydrocarbon fuels are used, mostly due to the need to reform and clean these fuels, and subsequent parasitic losses. As a result, heavy duty internal combustion engine-generators are probably more efficient. High temperature fuel cells provide better integration with the fuel processing equipment, and have higher tolerances for impurities in the fuel. Especially when combined with gas turbines or reciprocating engines, these fuel cell systems can attain higher electrical efficiencies than conventional generators.

Competitive power densities have already been demonstrated by some fuel cell car developers with hydrogen-fuelled LTPEMFCs, as this is an important development objective for automotive application. The power density achieved by high temperature fuel cell systems is lower, which is partly due to the increased BoP and heat insulation. However, a Ragone chart comparison showed that fuel savings by high temperature fuel cell systems and the higher energy density of hydrocarbon fuels result in a more compact system when operation over several dozens of hours is required. The total volume of a LT-PEMFC plant with cryogenic hydrogen storage is shown to be 1.5 to 5 times larger than alternative options for vessels with refuelling intervals over 100 h.

Load transient capabilities of fuel cell systems have a similar dependence on the fuel cell type and fuel processing requirements.

In general, systems with a large BoP and thermal mass have longer start-up times and limited load-following capabilities. Therefore, hybridisation with auxiliary electricity storage components, such as batteries, supercapacitors or flywheels will be required in many cases to meet maritime power requirements.

Various assessments have shown that fuel cell systems can achieve a lower environmental life cycle impact than diesel engine-generators sets, mainly due to reduced local emissions during their operational life time. However, the manufacturing stage has a relatively large impact, and the environmental gains depend on the life time of the stacks and recyclability of stack materials. High temperature fuel cells have a clear potential to reduce greenhouse gas emissions over their life cycle due to the high efficiencies that can be achieved, even if fossil fuels are used. Their low temperature counterparts have this potential if renewable hydrogen is available.

Some classification standards have been developed for maritime fuel cell systems, but currently they do not provide a general approach for safety assessment of all fuel cell systems, and can be overly stringent. In particular storage and handling of volatile, low flash point fuels needs careful consideration. On the other hand, the high availability and the opportunity to distribute power generation over the vessel can improve the redundancy of electricity generation. This should be further studied for future classification standards. It is expected that fuel cell systems will remain relatively expensive in the near future. However, significant cost reductions have been demonstrated lately, and novel concepts have shown the potential to reduce investment costs even further. It is expected that price levels can be achieved where reductions in fuel consumption, emissions, noise and vibrations would justify the higher a higher capital cost.

VIII. CONCLUDING REMARKS

Fuel cell systems provide an efficient way to generate electricity on-board from a variety of logistic fuels, with few hazardous emissions. Liquefied hydrogen-fuelled LT-PEMFC systems provide a power dense solution for ships with mission requirements up to a dozen hours. However, for sailing times over 100 h the limited hydrogen storage density is expected to result in 1.5e5 times larger total system volumes compared to alternative systems with more energy dense logistic fuels. High temperature fuel cell systems can achieve high overall system efficiencies using various hydrocarbon fuels, especially when equipped with bottoming cycles. Such systems can attain relatively low emission levels and reasonable density for ships with mission requirements of several days. For vessels that require longer independent operation, ship owners may face a trade-off between smaller fuel tanks using a dense logistic fuel, such as diesel, and fuel savings using a less energy dense gaseous fuel, for example NG.

Several challenges will have to be addressed before fuel cell systems are able to meet all maritime power requirements and can compete with state-of-the-art maritime solutions. The following topics are identified as most interesting for immediate further study:

_ The increasing availability of LNG and the rapid development of NG-fuelled fuel cell systems justifies maritime demonstration of such systems;

_ Fuel cell combined cycles have the potential to attain an even lower fuel consumption. Combining SOFCs with reciprocating engine generator sets seems particularly interesting for near future maritime application;

_ Hybridisation with auxiliary electricity storage components, capable of following the demanded load transients, requires further development;

_ Classification standards on opportunities to increase the redundancy of power supply with distributed electricity generation should be investigated.

Currently available fuel cell systems are significantly more expensive than conventional generators, but it is expected that system prices can be reduced to levels where the higher investment cost is justified by the advantages. These benefits stand out for vessels which operate in ECA zones, since exhaust gas cleaning is avoided entirely. LNG fuelling is already being adopted for these ships to meet stringent emission requirements.

Although environmental benefits from LNG as a logistic fuel
are debatable from a total life cycle perspective, NG-fuelled fuel cell systems have a relatively advanced development state, and the application of SOFC combined cycles can further improve the well-to-wave efficiency. In addition, most alternatives, such as hydrogen, MeOH and DME, are currently produced from a fossil feedstock, and NG can be produced from renewable sources as well. The authors envision that the developing LNG infrastructure and development state of NG-fuelled fuel cell systems can facilitate the introduction of gaseous fuels and fuel cell systems on ships.

Therefore, the development of a maritime LNG-fuelled SOFC reciprocating engine combined system will be taken up in the recently commenced Dutch national Gas Drive project.

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