Fuel cell technology for ferries.

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INTRODUCTION

Norway has been and still is an important shipping nation. With more than 12 000 vessels along the coast, the domestic ship traffic accounts for about 10% of the CO_2- and close to 40% of the NO_x-emissions in Norway. The Norwegian economy and welfare state is founded on energy resources, initiated by the substantial construction and development of hydro-electric power stations more than a century ago and later the exploitation of oil and gas resources in the North Sea from the late 60s.

The oil production has levelled out, but the natural gas (NG) production is still increasing. Norway is the largest producer and provider of NG in Europe. Domestic utilisation of NG has been put on the political agenda. The recent development and drastic improvement of the Fuel Cell (FC) technology along with highly competent research groups altogether form the rationale to study fuel cells for ships.

As a case study for fuel cell installation on board an existing ferry the natural gas powered ferry “Glutra” has been chosen. This ferry has a capacity of 100 pbe. (pbe= personal vehicles equivalent). A photo of the 100 pbe gas-electric “Glutra” is shown in Figure 1.

Figure 1 “Glutra” – The first natural gas engine powered ferry in the world with “gas-electric” propulsion system.

The ferry was presented in detail on the IMTA conference in Seattle, so I will not go in to detail about the ferry and the machinery arrangements

Introducing a fuel cell system into the ferry, the following additional systems should be considered:
- Fuel cell system
- Fuel storage system
- Fuel transfer system
- Fuel processing system
- Refueling system
- Electrical storage

Basic design parameters for these systems are further described below.

On diesel electric ferries the main engines normally is situated below main deck, but on "Glutra" however, an alternative design has been chosen due to application of natural gas as fuel. In this ship the main engines are situated on the boat deck (above main deck). This arrangement has been developed to comply with existing regulations from The Norwegian Maritime Directorate (NMD) for gas operation.

It is likely that a fuel cell installation on board will have to meet the same regulations, and that the general machinery arrangement of an existing ferry has to be revised and that fuel cells and auxiliary systems should be installed above main deck. Therefore, the ferry requirement for FC operation is based on the design parameters of "Glutra".

Fuel cell system requirements.

Marine applications introduce a set of requirements for fuel cell (FC) systems. These reflect the special conditions experienced at sea (such as movement due to waves, saline air etc.) and the need to be compatible with the conventional power systems on board the vessel. The latter puts certain restraints to the FC system with regard to power quality and dynamics. Further, any installation should be in compliance with current regulations.

<u>System requirements</u>
- Total FC system shall fit in a 20-foot container.
- The container shall be installed above main deck.
- The prime fuel for the system is Natural Gas (NG) and the power output shall be AC electricity (see Power requirements below).

- If needed, any installation (e.g., reformer) for converting NG to Hydrogen will be considered a part of the system.
- The system shall be self-sufficient with respect to internal water management, cooling etc.
- The fuel cell system shall not rely on supply of electricity or any other form of support from the main propulsion or existing power generation system.
- A small backup/buffer system (battery) shall maintain the system operation or facilitate shut-down procedures in accordance with safety requirements and regulations.
- The system shall sustain harsh seawater conditions including high air salinity and humidity
- The dynamics of the FC-system shall be in compliance with the demand of the auxiliary systems components and if needed a buffer system should be included.
- The FC system shall provide 50-100kW$_e$ nominal power.
- The power output should be variable in the range of 25-70 kW$_e$.
- The electrical power shall be 230Volt AC, 50 Hz.

Fuel storage - general arrangement

Fuel storage on an existing ferry design has to comply with existing regulations from NMD. Alternative fuel storage for fuel cell application is:

- Metal hydrids
- Liquified H_2, (LH_2)
- Compressed H_2, (CH_2)
- Other H_2 carriers as natural gas, methanol, etc.

In this project natural gas is chosen as the H_2 carrier and the natural gas system on board will be used as fuel for the fuel cell system.

Fuel processing and transfer system – general arrangement

The fuel transfer system connects the fuel storage tank to the fuel cell system, and shall comply with existing regulations from NMD. Main components in this system are: piping, valves, alarm system, shut-off system, inert gas system, etc. The piping shall go through existing casing for pipes if the storage is below main deck.

A double piping system is required for transfer of gaseous fuel. In case of leakage, the double pipe system shall be ventilated to the top of a mast beam above highest point on the ship. In all spaces and voids, which may be exposed to gas leakage, a gas detection and alarm system is required.

The original natural gas piping system on board will be used. This system will supply natural gas at a delivery pressure of app. 4 bar to the fuel cell system.

<u>Fuel processing system</u>

A natural gas processing system (reformer) may be required unless MCFC or SOFC will be used. This unit should be specified together with the fuel cell.

<u>Refueling system</u>

In general the refueling system shall be easy to operate and no needs for specific operations shall be required. The refueling system is dependent on the fuel storage system. During refueling no spill of ignitable gas is allowed.

The natural gas refueling system of "Glutra" will be used without modifications.

<u>Safety</u>

All safety measures shall be included in a fuel cell installation to ensure safe operation. This includes operational procedures, design and auxiliary system as inert gas system.

<u>Rules and regulations</u>

The ferry shall comply with existing rules and regulations for new-buildings of conventional ferries in Norway. In addition the ferry shall comply with NMD regulations "Regulations for building and operation of gas-powered passenger vessel" ("Forskrift for bygging og drift av passasjerfartøy drevet med gass").

The ferry shall also comply with IAC 60079-10, part 10: "Classification of hazardous areas", (see description in §6 –6.1.5 in above NMD regulations).

~~3~~Criteria for selection of FC type.

The following criteria for the selection of a fuel cell (FC) system for a Norwegian coastal ferry have been reviewed and are listed below:

a) Safety
   The current stringent regulations for all marine systems should not by any means be compromised. The safety should be ensured through regulations and products that are subject to approval from authorities. The inherent level of safety for each FC-type should be considered.

b) System efficiency
Reduction in emissions is the rational for the whole project and hence the second most important criteria. System efficiency is the key to reduced emission and pollution. Efficient fuel utilization is linked to the environmental effect, especially through CO_2-emissions. It should also be remembered that fuel cells eliminate the NOx emissions.

c) System costs
The present cost of the system is crucial for the realisation of a demonstration project. The total operation cost including operation (fuel) and maintenance (labour and spare-parts) should be considered. In cases where there is a trend towards substantial system cost reductions this should be taken into account upon FC-type selection. A slow degradation rate of the system with time is required (i.e., long life-time[1]). High complexity of the system will increase the installation costs and also influence the maintenance cost of the system. In addition, increased fuel utilisation will reduce operation cost.

d) Future technology improvement potential
Future technological breakthroughs are hard to predict. Still these are important for a correct choice of FC system. Due to the characteristic features of the respective fuel cell types, they have different potentials for improvements with respect to e.g., cost reduction, efficiency improvements etc. Each technology's potential for improvements should therefore be identified and considered.

e) Start up / transient response
A short start up time is favourable. The transient response time upon load changes for a power system is closely linked to operation safety of the whole ship. Delays in response may be problematic in critical situations. An adequate system should therefore be able to react without delays that compromise safety or reduces the comfort.

f) Power supply reliability
The reliability of a FC-system may be revealed through extensive testing (like for the PAFC) or through warranties from the suppliers. The complexity of a system,

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[1] Assuming 18 hours operation time per day for a Norwegian coastal ferry the yearly operation time is 6570 hours. A typical criterion used when considering FC-system life-time is a 10% performance degradation (reduction) at nominal power output. The lifetime of the system should be as high as possible (preferably more than 3 years normal operation). Maintenance of the system should preferably be performed at the same time and with the same time intervals as the ship maintenance is taking place (usually every year).

however, generally influences the reliability through the number of components that may fail. A pressurised system is inherently less reliable than an atmospheric system, but exhibit an increased power density. Direct conversion of NG to electricity is advantageous because the reformer is eliminated. Reliability is closely linked to safety, and safety requirements might dictate a certain degree of reliability.

g) Power density
Incorporation of a FC-system in a ferry should be held against the future possibility of using FC's for the main propulsion system of the vessel. Power density (kW/liter and kW/kg) is not only important with respect to the space and volume available on board the ferry. High Power density may be the key to reduced FC stack cost because it reduces the amount of materials needed.

h) Technology availability
Different FC types have reached different levels of development. The availability (and delivery time) of FC stacks and auxiliary components needed to assemble a system may dictate the selection of a FC technology that in the long term perspective may be inferior to others. Therefore, availability is crucial especially if the demonstration project should be realised in a short-term perspective. The present and future power range of available products should be evaluated.

As indicated many of the criteria listed above are highly interrelated. It is considered inadequate and unfeasible to give each criterion a certain weight and based on that, provide a total score for each technology and supplier. Therefore, it is important to hold each FC type and supplier against each criterion, and make an overall evaluation as to which types are viable and which suppliers are found capable of delivery.

4 Characteristics of Fuel Cell types

Fuel cells (FCs) convert chemical energy in a fuel (usually hydrogen gas) directly into electricity in an electrochemical process. The FCs are named after the type of electrolyte separating the anode from the cathode. The PEM fuel cell uses a polymer membrane, the AFC an alkaline (KOH) solution, the SOFC a solid oxide, the PAFC a phosphoric acid immobilised solution and the MCFC molten carbonate salt as electrolyte. This large variety of materials results in highly different operation ranges and system components.

Table 1. Key parameters for the 5 main fuel cell system types

	Low-temperature cells			High-temperature cells	
	PEMFC	**AFC**	**PAFC**	**MCFC**	**SOFC**
Electrolyte	Ion exchange membrane	Mobile or immobilised alkaline solution, KOH	Immobilised liquid, Phosphoric Acid	Immobilised liquid Molten Carbonate	Ceramic
Charge carrier	H^+	OH^-	H^+	CO_3^-	$O^=$
Temperature range	20-90 °C	0-80 °C	100-250 °C	~650 °C	600-1000 °C
External reformer for CH_4	yes	yes	yes	no	no
Prime cell Components	Carbon based	Carbon based	Graphite based	Stainless steel	Ceramic
Catalyst	Platinum	Platinum or non-noble	Platinum	Nickel	Perovskites
Water management	Evaporation	Evaporation	Evaporation	Gaseous products	Gaseous products
Heat management	Process gas + Independent Cooling media	Process gas + Electrolyte circulation	Process gas + Independent Cooling media	Internal reforming + Process gas	Internal reforming + Process gas
Typical Power Range	W-300kW	W-20kW	50-200kW 11MW[3)]	300-3000kW	1-3 kW[1)] 100-1000 kW[2)]

1) The new generation flat plate SOFCs developed for combined heat and power (CHP) for residential applications and APUs for automobiles (typically operating at 600-800°C).
2) The tubular SOFCs developed by SIEMENS Westinghouse for stationary power production (800-1000°C).
3) A stationary PAFC power plant was built and ready in January 1991 at Tokyo Electric Power Company (TEPCO) in Tokyo, Japan. The plant was rated at 11MW$_e$.

Technological evaluation of the FC types and their feasibility

Due to many advantages with respect to emission and efficiency, FCs have developed into a number of different types covering widely different markets and application in the range from W to MW.

As shown in Table 1, the five FC types have different characteristics. The large difference in the operation temperature should be noted (0-1000 ^oC). Classically, FCs are divided into two categories, low temperature fuel cells (0-250 ^oC) and high temperature fuel cells (600 – 1000 ^oC)

Low temperature fuel cell systems will need high purity H_2 that dictate the incorporation of a reformer as well as a gas clean-up system to remove CO from the synthesis gas (H_2, CO and CO_2). Such systems have been developed with success but the systems are voluminous and so far costly due to the complexity and the use of noble metal catalysts.

From a technical point of view, the high temperature FC technologies are better suited for the NG-fuelled coastal ferry application. This is due to their ability to convert NG directly or operate on partly reformed fuels. A technical evaluation of the 5 FC types and their feasibility for the coastal ferry application is performed with respect to the criteria listed above.

- SOFCs have originally been developed for large stationary applications (>100kW_e). However, due to recent developments of flat plate cells that tolerate lower temperatures, a new marked is opening for the SOFC in the kW range. These cells are meant for residential applications and as Auxiliary Power Unit (APU) in e.g., passenger cars, the latter demanding high power densities. These small-scale flat plate SOFCs might eventually reach the 50kW_e size, but it is expected that this will take 2-3 years. This makes the SOFC interesting for our application in the medium term perspective. The development of the flat plate cells is still in the prototype stage and a full range of products is not anticipated before 2005.

- MCFCs have been demonstrated for large power units (300 kW and upwards) only. The technology is not considered viable for small-scale applications.
  For MCFC some large-scale development programmes have been carried out for FCs used in naval ships. As for all military applications, cost is not an issue.

- PAFCs have been marked ready for almost 10 years. The high price is linked to the use of porous Teflon bonded carbon electrodes with high catalyst loading.

Only noble metal catalysts can be used in these cells. It is believed that, in the long run, the PAFC will not be able to compete with the other FC systems.

The PAFC is past the prototype development stage and a full range of products are commercially available. US Department of Defence (DoD) has more than ½ million operation hours on PAFC systems [International Fuel Cells are leading this development technologically and are able to deliver systems based on 200 kW_e units running on natural gas.

In Japan there are PAFC developers, which provides systems with high reliability. Four different PAFC systems (FP50 and FP100 from FUJI Electric, PC25 C from Toshiba and MP200 from Mitsubishi) have been evaluated by Tokyo Gas. Tokyo Gas still operates the worlds largest fuel cell system, a 10MW PAFC-plant (originally rated at 11MW). A total of >800.000 operating hours are obtained on PAFC-systems. Some units have operated for more than 8000 hours per year. FUJI Electric's technology has shown the best availability (>99%) compared to the late versions of the PC25 at around 95%. In average the availability of the power from these PAFC-units has exceeded 90% since mid 1998 except for the early versions of the PC25 C-unit. The performance degradation was only 10% within the 40.000hours of operation. The power was delivered at a very high quality (Voltage ±1% and Frequency ±0.01%). In the cases of system shutdown, the reason was primarily related to the auxiliary system components:

- PEMFCs have in recent years been developed and high performance at low noble metal loading has been demonstrated. Further cost reductions is also anticipated with increased mass manufacturing, reduced material costs and lower catalyst loading.

  The development of the PEMFC technology is lead by North American companies such as Ballard Power Systems and Plug Power, but a large and increasing number of companies are involved. The systems have shown very high power density and are currently the most studied fuel cell system.

- AFCs are mainly considered for smaller power applications. Some large units have been produced (for military and aerospace applications) at very high costs using pure hydrogen / oxygen and noble catalysts. Comments to the criteria listed in Chapter 3 for AFC:

  As a low cost system the AFCs are attaining renewed interest. 5-10 companies are involved in AFC development. The European company ZeTek Power was leading the development, however, due to the uncertainty of this company the technological advancement has been somewhat set back.

~~4.2~~FC-activities relevant for ferry applications

No FC-System has been tested on board of seagoing merchant vessels so far. In addition to the projects initiated by the Public Road Administration in Norway the current status of marine FC development is as follows:

- The most relevant marine application is the HDW/Siemens 250 kW hydrogen/oxygen PEM-FC System installed in HDW U-212 class submarines. Currently more than 10 submarines are on order (Fig. 5). HDW is working on a Methanol reformer for the next generation of submarine FC-Systems.
- Developments for civil marine applications are known from HDW and MTU Friedrichshafen.
- A consortium around STN-Bremen is developing a remote operated vehicle (ROV) which will use a PE-FC developed by ZSW in Stuttgart. The project supported by the German Ministry of Research named DeepC will be finished with the test of a technology demonstrator in 2003.
- The US Marine Administration (MARAD) supports the development of a power barge for the power supply of the hotel load for ships during port operation. In a first phase of the two-phase project a test installation had been run with two 200 kW PA-FC. The shiploads were simulated during the tests. In phase two the erection of a demonstrator including is intended.
- The US Office of Naval Research (ONR) proposed a demonstrator project to develop a 625 kW MCFC system using diesel oil as fuel. In 2001 the R&D phase was announced to last 6 years ending with a demonstrator.
- In Iceland the government is intending to substitute fossil fuel by hydrogen produced from thermal energy available in Iceland at low cost. Projects with buses using hydrogen as fuel are running. The fishery fleet is one of the major fossil fuel consumers in Iceland. It is proposed to use FC technology instead of diesel engines for fishing vessel power supply.
- The European Commission (EC) is supporting a pilot study named FC-SHIP. The project will start in June 2002. More than 20 companies and institutions including the Fincantieri yard, engine manufacturer MTU, the research companies SINTEF and MARINTEK and the class societies DNV, GL, LR and RINA are participating. The project is co-ordinated by the Norwegian Ship Owner's Association (NSA). It is intended to define the basis for the development of FC-Systems for merchant ships. Transfer of experiences from land based projects to marine applications, measurement of real life load requirements, definition of basic safety and operational requirements, a conceptual ship design for a passenger ship and the assessment of infrastructure requirements are main topics.

4.3Conclusion.

The best fuel cell technology for auxiliary power- ferry application.

As shown there are in principal 3 systems suited for this application (the PEMFC, PAFC or the SOFC). For realisation of a 50kW FC auxiliary power system within 1-2 years the PAFC and the PEMFC technologies are considered best suited. In the long perspective with further development of planar SOFCs this cell type is considered a better option for our application due to its capability of direct conversion of NG.

The following conclusions were made:

- Considering efficiency, power density and future cost estimates the PEMFC is considered as the best technology.
- When fuel flexibility is considered the SOFC is the best technology due to the possibility to convert natural gas directly to electricity.

There is a considerable uncertainty with respect to the time for the realisation of this demonstration project. Therefore, at least 2 FC types (PEMFCs and SOFCs) should be considered for the 50kW range. If certain research related bottle-necks (e.g., the need for an air-scrubber to remove CO_2 from the air) the AFC might become a viable cell type for the 50 kW_e range.

4.4The best fuel cell technology Full scale FC system in the 1.5 MW_e range

For a full scale FC powered Coastal Ferry (requiring typically1.5 MW_e propulsion power) in which the FC constitute the only power conversion technology on board, the requirements with respect to reliability and dynamic response time are stricter than for a auxiliary system. The high power output also puts restraints on power density. Reformers are typically large and bulky, and hence such components should be avoided. Based on these reflections high temperature fuel cells (SOFC and MCFC) are viable and especially advantageous for the full-scale application. For this power range, the MCFC also constitute a viable option.

Installation

The drawings below indicate where a PEM fuel cell have to be installed onboard "Glutra", and how it is connected to the existing machinery systems. The fuel cell container also includes a reformer and an air pre-treatment system.

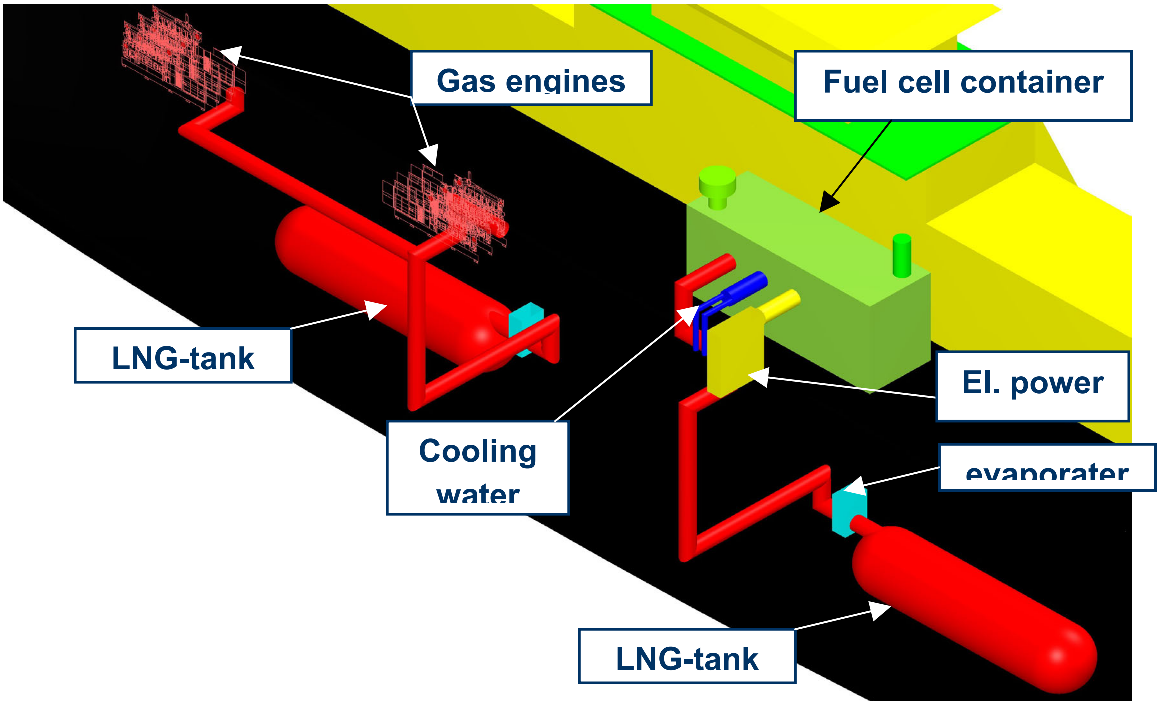

Figure 2. A PEM fuel cell installation onboard "Glutra"

Concluding Remarks

Fuel cell technology is on its way to find a market in the power supply sector. All manufacturers announce competitive systems for the second half of this decade. In the moment a large number of pilot applications are either running or under design.
For merchant ships pilot projects can be expected in the next years.

In a short term (a 10-20 years period) the fuel cell technology is not an alternative for merchant shipping due to:

- high investment costs.
- facilities for a large scale production of hydrogen is not existing (should be combined with CO_2 depositing in large offshore structures)
- a not existing distribution network for hydrogen.
- cheap fossil fuels
- safety

In a short term use of natural gas is a good solution for many ship operators. The investment cost is a little bit higher (5-15%), but the life cycle cost is lower. In addition use of natural gas reduce the NOX emission with 90% compared to marine diesel oil and no emission of particulates and HC.

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