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Bio-methanol Fuel Cell Systems for Ships

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1 Introduction

On board of ships electricity is usually generated by diesel generator sets. Ship operators are however more and more confronted with emission regulations. Emission of NOx, SOx, particulate matter (PM) and volatile organic compounds (VOC) are becoming increasingly restricted, especially in ports. Besides that, the idea that a very expensive climate crisis is coming towards us is becoming more and more accepted. This results in an increasing focus on reduction of greenhouse gasses, especially CO_2. For the near future (less than 5 years) it may be relatively easy for ships to fulfil the emission regulations. However, this is much less certain for the midterm future. A possible solution to produce electricity on board ships without any harmful gaseous emission is to use fuel cells fuelled by a renewable fuel [1]. A very promising fuel would be bio-methanol which is produced (e.g.) from glycerine, a waste product from biological origin. Fuel cells might provide a very efficient means of converting this bio-fuel into electricity.

2 Fuel Cells on Board of Ships

Fuel cells are being developed for decades. The focus has mostly been on automobile applications and stationary electricity and heat generation. As an example, figure 1 shows a Mercedes Benz A-class car equipped with a methanol-fuelled fuel cell system at the finish of a 12 days, 3000 miles+ test drive across the United States.

Figure 1: Mercedes Benz A class with methanol fuelled fuel cell system [2].

The use of methanol as fuel for fuel cell cars was a topic of significant R&D in the 90’s of the previous century. Methanol as fuel was abandoned in those days for reasons of safety and health, in particular related to possible contamination of water. This is an issue related to the consumer use of methanol fuel. For application of methanol as fuel for ships this is not a serious issue as it is a much more industrial application, not a consumer related issue. A number of studies have already been conducted for the use of fuel cells ships on ships and currently fuel cells are applied in a number of pilot and commercial projects. We believe that with our proposed system configuration a large number of different marine applications will become within reach. This case study provides answers to the following questions:

- What requirements does a fuel cell system have to fulfil for a given ship type and application?
- What would be the preferred system configuration? Which lifetime is required?
- What will the efficiency of the preferred system be and besides fuel, what other utilities are needed?
- What dimensions and weight will a possible system have?
- What constraints with respect to safety, regulations, fuel logistics etc there will be?
- What further steps are needed to develop such a system?

3 Project Organization and Tasks

The project was executed with a number of key partners, covering the shipbuilding industry, the ship operating industry, the fuel cell R&D and the safety and certification issues. *Damen Shipyards Gorinchem* (Netherlands), builds a large variety of ship types worldwide. The main task of Damen was to set up a program of requirements. *Wagenborg Shipping Delfzijl* is a ship operator and owns a large number of cargo ships. Wagenborg selected a representative ship type as a base case to integrate a methanol based fuel cell system and also advised on the basic requirements. *Energy research Centre Netherlands* (ECN) is a major European research centre focusing on energy research development and consultancy and has experience with methanol in relation to fuel cells. ECN's task was to assess the basic system configuration and determine the main parameters of such a system, being efficiency, dimensions and weight. *Ecofy*s is a consultancy company based in Utrecht in the field of energy savings and sustainable energy solutions. Ecofys summarized the main issues with respect to safety, regulations and fuel logistics.

4 Requirements and Starting Points

As benchmark for the fuel cell system a representative ship type from the Wagenborg fleet has been chosen. The vessel type is a multipurpose dry cargo carrier with a total loading capacity of approximately 7300 ton. A picture of such vessel is shown in figure 2, the MS Loireborg, built by Royal Niestern Sander, delivered in 2008.

Figure 2: The dry cargo carrier (7300 ton).

Although there is a large variation in dimensions of similar ship types, the electrical power system is thought to be representative for a lot of vessels. The electrical installation is shown in a one-line diagram in figure 3.

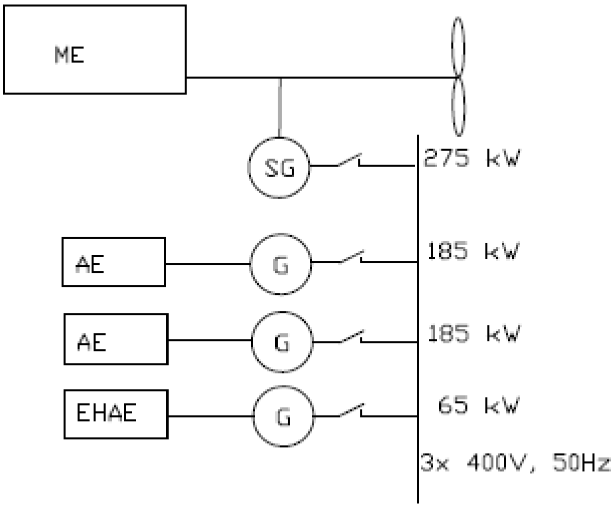

Figure 3: Electrical system lay out (NE=Main Engine, AE =Auxiliary Engine, EHAE=Emergency/Harbour auxiliary engine, SG= shaft generator).

The proposed fuel cell system will replace one auxiliary engine. When the vessel is at sea, usually the shaft generator is taking care for the total electricity supply on board. When the vessel is approaching a port, the auxiliary engines are switched on.

The *required lifetime of the fuel cell* was defined as 16,000 hr or about two years. As most ships have a maintenance interval of 2.5 years, this will also count for the fuel cell system. Within these 2.5 years the fuel cell system is expected to run more or less permanently. The *electric load balance* has been studied and yields a *nominal power* of 125 electrical kW and a *peak power* 185 electrical kW, this peak power shall be produced for a minimum of 5 minutes time. With these specifications a fuel cell system would be able to generate power for the majority of operations while in port. At the same time the total amount of installed power is enough in all situations. The fuel cell system should be arranged as the 'first' source of auxiliary power. In case the fuel cell system considers or expects the electrical load to be too high, the auxiliary diesel engine should be started up automatically. During switchover to sea-mode, the shaft generator should be able to take over from the fuel cell system. The exact utilization of the fuel cell system and shaft generator will depend on economic parameters. Concerning *power dynamics*, the maximum allowable variations in the power supply are defined as a variation in voltage between +6 and -10% of nominal voltage and a variation in frequency of: +/- 5%. The volume and weight of the fuel cell system should preferably not be beyond the size and weight of a diesel power generator. Other parameters as vibrations and ship motion (including deceleration in the case of a ship collision) are determined as well. Germanischer Lloyd has done a lot of work in the field of fuel cells and developed a complete set of descriptive rules which can be applied to the fuel cell system proposed in this study. The fuel cell system will need to obey all applicable *rules and regulations*.

5 System Evaluation

In the initial project phase, a choice was made regarding the type of fuel cell for this application. In principle, a choice can be made between DMFC, PEMFC, MCFC, SOFC and PAFC. Based on the applicable power range for this application and the availability of stacks, the PEMFC technology and SOFC technology were short listed as design case for this application.

The goal of the fuel cell system is to generate electricity from methanol. However, in order to utilize a PEMFC or a SOFC, the methanol feed needs to be converted (reformed) to a hydrogen rich gas. Reforming can be performed in two ways: by steam reforming or by auto thermal reforming. An advantage of auto thermal reforming is that dynamic operation is possible. However, in our application the system will operate stationary. Another difference between auto thermal and steam reforming is the efficiency. In general, steam reforming can be performed at higher efficiencies. Therefore, steam reforming is chosen as the preferred methanol conversion step. Figure 4 shows the conceptual lay-out of the PEMFC based system. The reformer product gas is sent to the preferential oxidation unit to reduce carbon monoxide to a level below 10 ppm CO in order to minimize degradation of the anode (noble metal) catalyst in the PEMFC.

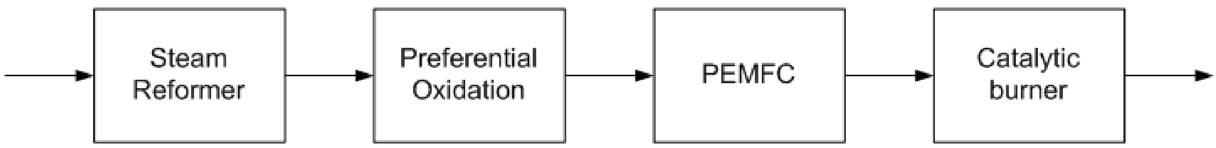

Figure 4: Conceptual lay-out of the methanol based steam reforming system.

The goal of the SOFC system is similar to the PEMFC system: To reform methanol to a hydrogen rich stream and utilize this to generate electricity. Here reforming is performed by steam reforming as well (figure 5). In this system there is no need for a gas clean up like preferential oxidation, because the carbon monoxide present in the reformate is not toxic, but rather a fuel for the SOFC. The SOFC system lay-out is therefore simpler. The SOFC is operated at high temperature (700-800 °C). Therefore, it is necessary to preheat the reformate before it enters the SOFC. The off gasses from the fuel cell are supplied to a burner. The heat generated in the burner is utilized for steam reforming as well as for heating up the reformate.

Figure 5: Conceptual lay-out of the methanol based steam reforming system.

In the PEMFC system and the SOFC system, batteries are included to secure the electricity supply upon significant demand increase (up to 54 kW). Both systems should be able to respond to such demand changes within ten minutes. Therefore, the required batteries should be similar for both systems.

6 Results and Discussion

The PEMFC system is presented schematically in figure 6, indicating that methanol and water are pumped into the system, heated, evaporated and supplied to the steam reformer (operating at 250 °C). In the steam reformer the following reactions take place [3–5]:

$$CH_3OH + H_2O \leftrightarrow CO_2 + 3H_2 \qquad \Delta H = +48.8\ kJ/mol$$

$$CH_3OH \leftrightarrow CO + 2H_2 \qquad \Delta H = +89.2\ kJ/mol$$

$$CO + H_2O \leftrightarrow CO_2 + H_2 \qquad \Delta H = -41.0\ kJ/mol$$

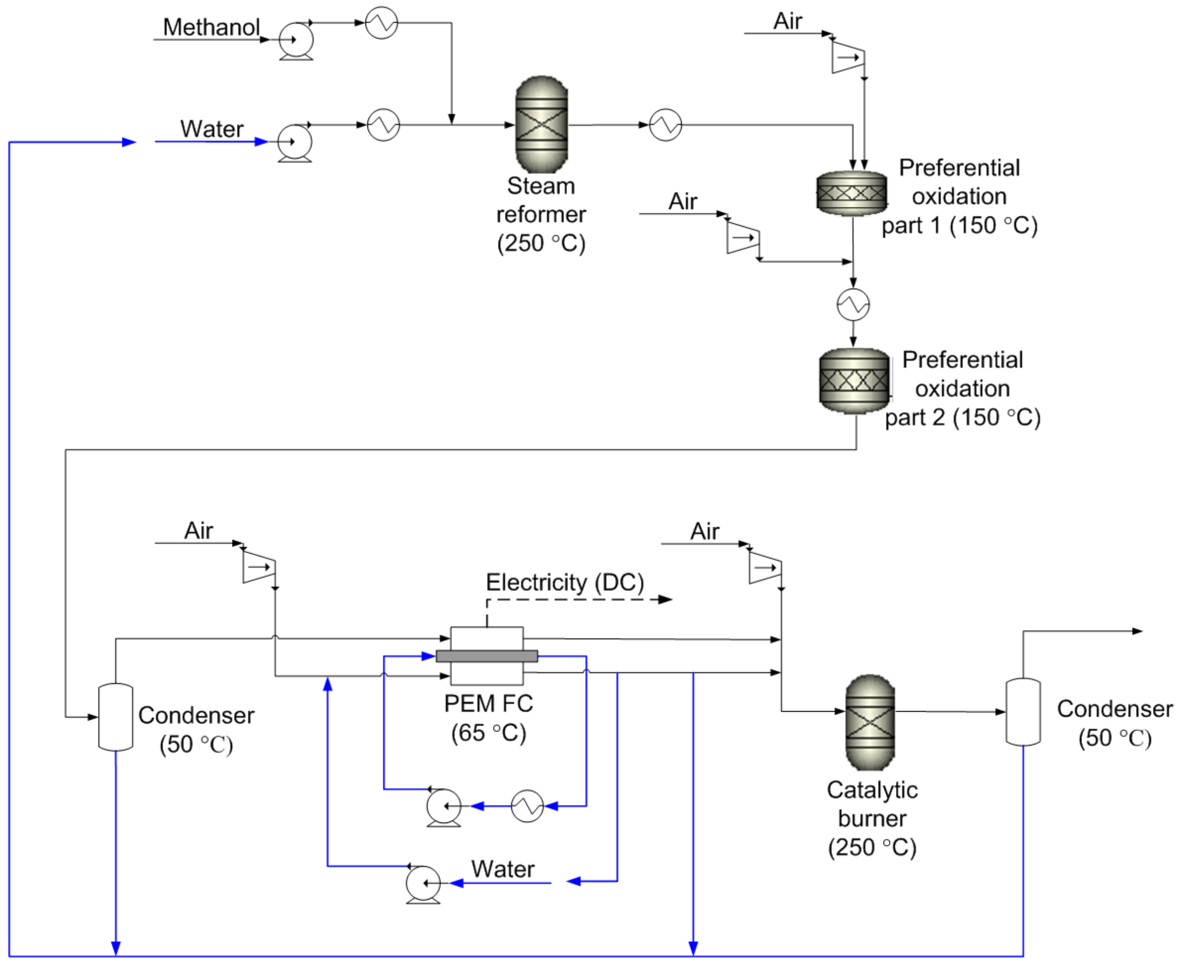

Figure 6: Conceptual flow scheme of the PEMFC system.

Reaction (1) is the steam reforming reaction, reaction (2) is the methanol decomposition reaction, and reaction (3) is the water-gas shift reaction. The first two reactions are endothermic, while the third reaction is slightly exothermic. The overall reaction in the steam reformer is endothermic, so that external heat has to be provided. The off gas from the catalytic afterburner will be cooled down from 250 ^{0}C to 50 ^{0}C, providing sensible heat for co-generation. Using the same methodology, also a design case with SOFC stacks technology was analyzed. The conceptual flow scheme is given in figure 7.

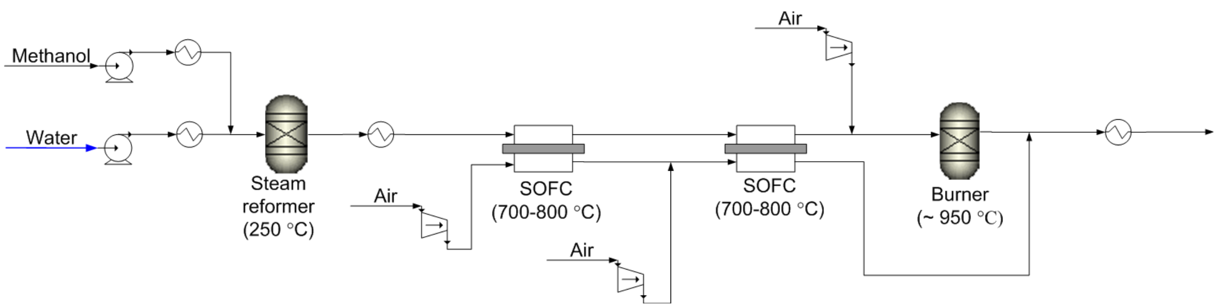

Figure 7: Conceptual flow scheme of the SOFC system.

In table 1 the main operating characteristics of the PEMFC and SOFC system are compared.

Table 1: Overview of simulation results.

	PEMFC system	SOFC system
Net electrical efficiency (%)	41.6	42.8
Total net efficiency (electrical and heat) (%)	41.6	69
Additional cold utility requirement (kW)	152	25
Water recycle possible (if pure methanol is used)	Yes	No

Table 2 shows the other system characteristics. Based on the availability and the lifetime of the stacks, the PEMFC case was selected as most promising option.

Table 2: Other system characteristics calculated.

	PEMFC system	SOFC system
Commercially available FC stack (kW)	≤ 100 kW	≤ 1 kW
Lifetime stack according to supplier (h)	20 000[1]	1 000[2]
Complete system size (m^3)	9.3	9.0
Fuel storage (pure methanol) (m^3)	51	50
Fuel storage (mixture) (m^3)	81	78

7 Conclusions and Outlook

The electrical efficiency of the SOFC system performs marginally better than the PEMFC (42.8 % versus 41.6 %, respectively). In terms of total system efficiency the SOFC system scores significantly better, as generated heat can be utilized to heat thermal oil on the ship for co-generation of heat. (69 % for SOFC in comparison to 41.6 % for the PEMFC). Beside the high system efficiency, there are also downsides to the SOFC system. Water supply will always be necessary for the SOFC system, as not all water can be recycled in the system. The PEMFC system can work without a water supply, if pure methanol is utilized as a fuel. Another downside of the SOFC system is that SOFC stacks are currently available to a maximum of 1-2 kW. This would mean that more than a hundred stacks would be necessary in the system. This is not practical. Furthermore, the lifetime of the SOFC stacks (1,000 h) is distinctly below the desired lifetime of 16,000 hours.

The size calculations indicate that the methanol storage is the most important factor in terms of overall system size. If a water-methanol mixture is utilized (instead of pure methanol) the size of the feed storage increases with about 60 % (from ~50 m^3 to ~ 80 m^3). The calculations also show that in terms of size, there is little difference between the PEMFC and SOFC systems.

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1 According to NedStack product information

2 According to Staxera product information

As an overall conclusion, we conclude that a PEMFC based fuel cell system as the most promising, with the generation of 125 kW at efficiency of 41.6% in a 9 m^3 system. Safety regulations and fuel logistics are important exogenic parameters that have to be taken into account. Furthermore, the proposed fuel provides a CO_2 neutral chain with no or hardly any harmful emissions, while the price of the methanol fuel is comparable to that of diesel oil.

A follow-up of the study presented here is the preparation of a complete design for a 185 kW methanol fuel cell system on board of ships, taking into consideration all required regulations that are inherent to a ship operation and to the safety of a hydrogen production unit in combination with a fuel cell. This follow-up is currently being investigated.

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