Energy balance of a Fuel Cell System for on board auxiliary power generation

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Abstract

In this paper a theoretical study of a ship auxiliary power plant driven by Fuel Cell technology is presented. The most suitable Fuel Cell type and operation is identified depending on the constraints that the ship auxiliary power plant presents. An energy balance is then calculated for the whole Fuel Cell system. The results of a study on Fuel Cell/ship auxiliary power plant are presented

Keywords: Fuel Cells, Marine Engineering

1. Introduction

Fuel Cell technology is seen as a promising alternative to the combustion engine to reduce air pollution due to its higher efficiency, in the order of 50-60 %. In the other hand the, usually, the volumetric power density of a Fuel Cell system compared to a conventional combustion engine is much smaller, up to 20 times in some cases. For this reason, when considering Fuel Cell technology for marine purposes, it is reasonable, to confine its use to on board auxiliary power generation, where the power demand is much smaller, and hence the resulting volume of the whole power system, will be not critically affected by the dimensions constraints that are present on board the ship main engine room.
When considering replacing the ship diesel engine generator auxiliary power plant with a Fuel Cell one, the following considerations are taken

<u>High power demand</u>: Although the power required for on board auxiliary power generator is much smaller than the one required for the propulsion of the ship, around 1-5 % of the total power, this demand can be quite challenging to meet with most of the conventional existing fuel cell systems. For large cases the required installed power can reach up to 3 MW.

<u>Fuel flexibility</u>: Fuel cells are designed to operate with hydro-carbonaceous fuels. The lighter is the hydrocarbon ratio of the fuel, the easier is to design the fuel cell system and the lower are their emissions (gram CO_2-MJ). In the other hand, light hydro-carbonaceous fuels can present storage difficulties, and safety issues on board a ship. Therefore it will be advantageous to consider a Fuel Cell System that can easily operate with a range of different fuels, allowing to create different, feasibility studies depending on the fuel use.

<u>Robustness and high system life</u>: Due to the complexity of operate, maintain and repair fuel cells compared to a conventional diesel engine generator, it is necessary to have consider a fuel cell system, that can operate for long period of times without required maintenance. Also the system must be robust, specially to sulphur poisoning, to avoid system failure during the ship operation.

System simplicity: As it was mentioned above, Fuel Cell systems are more complex to operate, than a conventional diesel engine power plant. Therefore having a very complex system will required the training of the marine engineers on board to be excessive complicated making perhaps, the system not feasible to operate as a substitute.

2. Auxiliary power plant and ship constraints

There are several types of Fuel Cells, which are categorized according to its electrolyte material. The most relevant ones are

PEMFC (polymer electrolyte membrane fuel cell): Polymer Electrolyte Fuel Cells (PEMFC) operate at between 60 to 80 C, which allow them to rapidly start up, but prevents them to use waste heat for cogeneration purposes as well as presenting a complex thermal management system due to its low temperature range. They use expensive platinum catalysts on the electrodes to accelerate the chemical reaction. These types of Fuel Cells are very sensitive to CO, S, and NH_3, therefore they are lend to use to situations where pure hydrogen can be used as fuel, unless expensive and complicated fuel cell reformers and desulphurization units are used in conjunction. They present a relative complex water management system, since the electrolyte membrane must be hydrated at all times but not flooded.

MCFC (Molten Carbonate Fuel cell): Molten Carbonate Fuel Cells (MCFC) operate between 600 and 700 C. They required carbon dioxide in addition to be delivered to the electrodes, and the electrolyte is characterized to be very corrosive presenting some material challenges.

SOFC (Solid Oxide Fuel cell): Solid Oxide Fuel Cells (SOFC) operate between 600 and 1000 C, therefore are considered as high temperature fuel cells. Its solid electrolyte permits to cast the cells into different geometries. The chemical reaction kinetics inside the Fuel Cells is relatively high compared to other types, and CO is used as a directly useable fuel. Although due to its high operating temperature a complex thermal management system is required, waste heat can be used for cogeneration. The cost of the materials used on Solid Oxide Fuel Cells is modest compared to other Fuel Cell types. These facts make high temperature Solid Oxide Fuel Cells one of the most promising alternatives to use on board a ship.

If hydrogen is assumed not to be used as the fuel cell system fuel, then the fuel cell stack should be coupled to a hydro-carbon reformer, that transform the fuel into a mixture hydrogen rich gas mixture. Although some high temperature fuel cells can directly reform some types of fuels inside their stack, this is not very convenient due to the thermal gradients usually formed inside the system cells. The most important types of hydrogen production technologies are

SMR (Steam methane reforming): Hydrogen production via steam methane reforming is achieved injecting high temperature steam to a hydro-carbonaceous fuel. For this case, a steam and heat source is required.

POX (Partial Oxidation reforming): Hydrogen is produced by injecting oxygen into the fuel. It is considered a fast process that release heat, although a relatively rich source of oxygen is required

ATR (Auto thermal reforming): Auto thermal reforming consists into a balance of the methods mentioned earlier. This balance is achieved when the net heat required is zero since steam reforming is an endothermic reaction and partial oxidation is an exothermic process.
Among the fuel cell technologies the most promising ones for marine purposes are the MCFC and SOFC. When considering the fuel flexibility and system simplicity constraints, PEMFC are out of consideration, since they cannot tolerate any source of carbon inside their stack. This implies to have a complex reformer that and clean up system that will convert first the hydrocarbon fuel into a

mixture of hydrogen and carbon compounds that latter will needs to be clean up converting the mixture into a very high rich hydrogen gas mixture.
MCFC systems can be considered to be simpler than SOFC, since in the majority of the cases they do not precise an external reformer, but in the other hand they precise higher maintenance due to its high corrosive electrolyte. Also MCFC need to re-circulate a fraction of the exhaust products rich in CO_2, into the Fuel Cell Stack, making the balance of plant of the system to be more complex. Therefore as a first attempt, SOFC can be considered as the most promising technology for on-board auxiliary power generation.
When using a high liquid hydro-carbonaceous fuel, such as diesel with a fuel cell system, the complexity of the Fuel Cell balance of plant increases drastically. Diesel reforming into a rich hydrogen gas mixture can be quite a challenging process; therefore the most suitable fuel to be used with a SOFC system will be natural gas that can be considered readily available.
As mentioned before, there are three technologies to be used for hydro-carbonaceous fuel reforming. The most suitable one is the SMR, since it does not require a source of oxygen, like the other two technologies, simplifying the technology substantially.

3. Fuel Cell System components operation

The system considered for on board auxiliary power generation is a Solid Oxide Fuel Cell System coupled with and external Steam Methane Reformer.
The fuel that has been considered is natural gas with the following properties, Campanari S, (2000).

Table 1: Natural Gas Properties

Fuel Properties			
Compound	**Formula**	**Percentage (Molar)**	**Total Flow(kg/s)**
Methane	CH_4	81.30	0.0055
Carbon Monoxide	CO	0.90	**Combustion Heat (kJ/kg)**
Nitrogen	N_2	14.30	38423.8
Ethane	C_2H_6	2.90	
Propane	C_3H_8	0.40	
n-Butane	C_4H_{10}	0.20	

In the following figure, the Fuel Cell System different components can be seen, as well as the mass and energy distribution being represented by solid and dashed lines respectively.

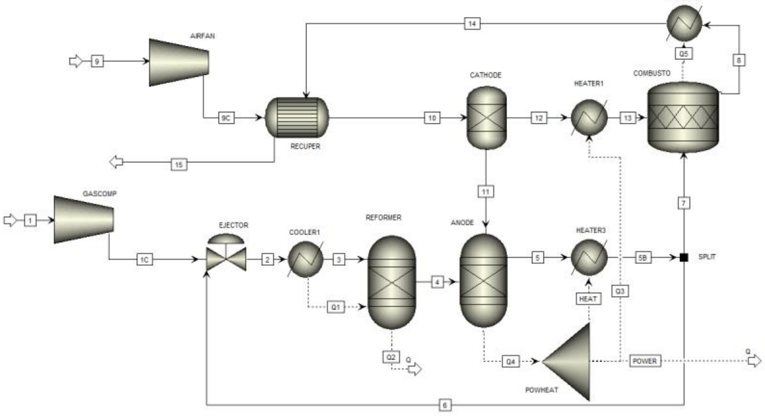

Figure 1: Fuel Cell System components

Fuel and air compressors

The fuel is compressed to 3.24 bars, Campanari S, (2000), to overcome the pressure drop exerted by the Fuel Cell systems. The Fuel Compressor is considered as an isentropic unit with an efficiency of 72%.

The air required to react with the hydrogen internally produced both at the reformer and the fuel cells stack, is considered to be a molar mixture of 21% O_2 and 79% N_2, with a mass flow rate of 0.33 kg/sec and initial temperature of 25 C. This air is also compressed to the operating pressure of 1.08 bars with an isentropic compressor with a total efficiency of 72 %.

Mixer

Is in the mixer where the high rich steam products from the fuel cell mix with the incoming fuel. This steam feed is required to break the gas molecules into a mixture of hydrogen and carbon compounds.

Pre-reformer

Although direct reforming can be performed inside the fuel cell stack, it is desirable to reform, some of the fuel prior entering, to avoid large thermal gradients along the cells of the system. The set of reaction considered on the pre-reformed are:

Steam reforming reactions

$$C_nH_{2(n+1} + n\ H_2O \leftrightarrow n\ CO + (2n+1)\ H_2 \quad (1)$$

Water Shift Reactions

$$CO + H_2O \leftrightarrow CO_2 + H_2 \quad (2)$$

The stoichiometric yield of the reaction has been estimated by minimizing the Gibbs free energy of each of the set of the reactions.

Fuel Cell Stack

The reactions considered on the fuel cell stack are, the steam reforming, and water shift reactions, equations (1) and (2) as well as the electrochemical reaction

$$H_2 + 1/2\ O_2 \rightarrow H_2O \quad (3)$$

This reaction is the one that liberates electrons producing the electricity, and hence the power output of the fuel cell system. As same for the reformer, the stoichiometric balance of the reactions has been estimated by minimizing the Gibbs free energy of the set of the reactions.

Recirculation System

The recirculation system consists of a vacuum pump that recirculates about 50 % of the Fuel Cell Stack products into the reformer. The Fuel Cell Stack products are rich in steam and also at a high temperature. This heat is necessary due to the high endothermic nature of the steam reforming reactions.

Combustor

The combustor is treated as a stoichiometric reactor where, a complete conversion of the reactants is assumed. The reactions considered are

Hydrocarbon combustion

$C_nH_{2(n+1)} + (n+1)/2\ O_2 \rightarrow n\ CO_2 + (n+1)\ H_2O$ (4)

Carbon monoxide combustion

$CO + 1/2\ O_2 \rightarrow CO_2$ (5)

Hydrogen Combustion

$H_2 + 1/2\ O_2 \rightarrow H_2O$ (6)

In the combustor, the unreacted fuel remaining on the exhaust products of the Fuel Cell Stack are burned, increasing the temperature of the exhaust gas.

Recuperator

The incoming air to the Fuel Cell Stack is preheated to its operating temperature on the recuperator. In order to avoid a temperature decrease on the fuel cell, as well as large thermal gradients, the air feed to the fuel cell needs to be heated. The recuperator is modelled as a conventional counter current heat exchanger using the LMTD method, where the cold stream outlet temperature is specified.

4. Fuel Cell voltage calculation

When estimating the performance of a Fuel Cell System, the voltage output produced by each of the cells must be carefully calculated. The cells inside the stack are a low voltage device that produces about 0.6 volts for about 160 W of electric power. Therefore the cells are connected in series to increase the voltage of the system. Since the voltage output of each of the individual cells can be assumed to be uniform, it must be calculated with special detail in order to avoid severe errors on the calculation of the system performance

The voltage output of the Fuel Cell system is hence the voltage of each of the cells assumed to be uniform, multiply by the number of cells

$$V_{out} = \text{number of cells} \times V_{cell} \quad (7)$$

The output of each of the cells is calculated based on the electric power liberated by the reaction mentioned in the equation (3). This is called the reversible voltage which is calculated by the maximum available work according to the Gibbs free energy (9). Some irreversible losses, which are further described later, must be subtracted to this theoretical electric power. Hence the voltage produced by each of the cells can be calculated as

$$V_{cell} = V_{rev} - V_{irrev} \quad (8)$$

The reversible voltage based on the Gibbs free energy by the reaction (3) can be written as

$$V_{rev} = V_{nerst} = E^0 + \frac{RT}{2F} \ln\left(\frac{P_{H_2}\sqrt{P_{O_2}}}{P_{H_2O}}\right) \quad (9)$$

The irreversible losses are divided into activation, ohmic and concentration losses, dropping the efficiency of the Fuel Cell from 83% to 50% approximately

$$V_{irrev} = V_{act} + V_{ohm} + V_{conc} \quad (10)$$

In order for a reaction to take place, an energy barrier must be overcome, producing a voltage loss which is described by the activation loss, according to Nehter P, (2005)

$$V_{act} = \begin{cases} \frac{RT}{nF} \ln \frac{i}{i_0}, \text{for } \frac{F}{nRT} V_{act} > 1 \\ \frac{RT}{nF\beta} \frac{i}{i_0}, \text{for } \frac{F}{nRT} V_{act} < 1 \end{cases} \qquad (11)$$

The first term of equation (11) is used for high activation losses, when the current density is relatively low and the second term, when the activation losses are los
A voltage drop also occurs due to the internal resistance exerted by the porous materials of the cell. This can be expressed by Ohms law, Sanchez D, et al, (2006)

$$V_{ohm} = R_{cell} \cdot i_{cell} \qquad (12)$$

Finally the concentration losses occur due to the fact that the concentration gradients are different at the surface of the cell and at the reaction site. These voltage losses can be modelled according to Nehter P, (2005) as

$$V_{conc} = \frac{RT}{nF} \ln \left[\frac{P_{H_2}^{eff} / P_{H_2}^{tpb} \quad P_{O_2}^{eff} / P_{O_2}^{tpb}}{P_{H_2O}^{eff} / P_{H_2O}^{tpb}} \right] \qquad (13)$$

5. Energy balance and carbon emissions reduction

In the following graph the polarization curve based on the assumptions of the previous section can be observed. It can be noted that the system efficiency is directly related with the output of the cells inside the stack. Therefore the efficiency of the system is higher at low power demands. In reality this is lowered due to the Fuel Cell auxiliary systems operation at low power demands, Kanbabu K, et al (2007)

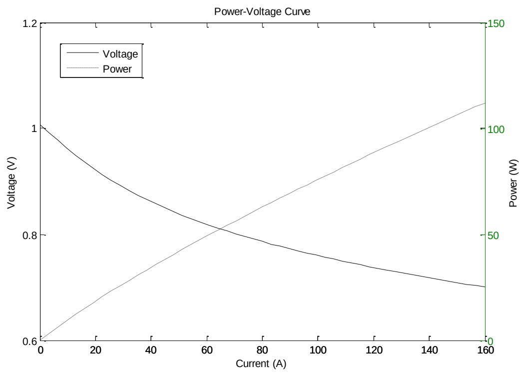

Figure 2: Cell polarization curve

In the following table, the energy balance of the Fuel Cell System considered is presented. The high temperature Solid oxide Fuel Cell is rated to produce around 100 kW of electric power. The 107.18 kW of DC electric power calculated for the system should be lowered when considering an AC power plant due to losses in the conversions.

Table 2: Fuel Cell System Energy balance

Fuel Cell System Energy Balance		
Component	Energy (kW)	Percentaje
Fuel (LHV)	210.42	-
Stack Electrical	107.18	37.44
Stack Thermal	179.08	62.56
Electrical Consumers		
Fuel Compressor	-1.56	-1.45
Air Compressor	-2.54	-2.37
Thermal Consumers		
Reformer	-21.57	-12.05
Recuperator	-91.90	-51.32
Fuel Cell System Energy Balance		
Electrical Efficiency	-	50.08
Thermal Efficiency	-	31.18
Efficiencies		
Fuel Cell System (LHV)	168.70	60.17

It must be noted, that the Fuel Cell systems provides also a greater amount of thermal power that can be used for cogeneration purposes. The relatively losses of the thermal plant are relatively large compared to the electrical ones due to the high operation temperature of the Fuel Cell System. This fact lowers the potential efficiency of the whole system, but the overall system efficiency is still higher than a conventional diesel engine generator based on the low heating value of the fuel.

6. Conclusions

The benefits of having a Fuel Cell System integrated within the ship power plant are analyzed by means of increasing the energy efficiency of the system. If a Fuel Cell system is integrated with the ship power plant is carried out for a high temperature solid oxide fuel cell system, the dimensions of the reforming units, thermal recuperators will be able to be reduced. Those units represent about 60% of the total volume of the Fuel Cell System.
The convectional way to consider a Fuel Cell System to generate on board electric power is to place a land-based Fuel Cell system, which is designed to operate at constant load, and install it directly on board a ship. This method provides a broad range of different configurations of the auxiliary power plant, since the Fuel Cells systems can be arranged according to the needs in a modular way. In the other hand, it is not possible to reduce the Fuel Cells dimensions which are about 20 times bigger compared to a diesel engine generator for the same power capacity, and also they must be operated at constant load, since the load transient time is very slow. In addition they must be kept also turned on at all times, since the start time, is extremely high.
If an external thermal energy flow is provided to the reforming units, the reactor operating temperature can be increased. With a steam reforming reactor operating at higher temperature, the rate of the reforming reactions (1) is higher, hence producing a greater fraction of hydrogen and a lower fraction of water. Therefore the partial pressure of hydrogen at the cell inlet will be higher and the partial pressure of water will be lower, having an overall effect of increasing the reversible voltage described by the Nerst equation (9).

A more straight forward correlation can be also applied to the recuperation units. Where the thermal energy used to preheat the incoming air to its operational temperature can be obtained from the ship power plant instead from the Fuel Cell system.

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