Fuel Cells for Marine Applications

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ABSTRACT

In this paper a theoretical study concerning the use of Solid Oxide Fuel Cells for ship auxiliary power plant is presented. Auxiliary power demand is estimated for a range of general cargo ships using a regression technique. The Fuel Cell design parameters are determined for a range of power requirements via a simulation model. Potential carbon emissions reduction by the use of Fuel Cells for a range of ships is estimated.

Keywords: SOFC, Marine Engineering

1. INTRODUCTION

Fuel Cell technology can be seen as a promising substitute to the traditional combustion engine when trying to mitigate carbon emissions on board ships

At the present time, Fuel Cells still present lower volumetric power densities compare to a diesel engine, this fact together with the existing Fuel Cell power range limited to several hundreds of kilowatts, confine their use in the ship auxiliary power plant as a first attempt. During the last few years some Fuel Cell installation have been carried out for marine purposes

Table 1: Marine Fuel Cells Installation Cases

Year	Country	Fuel Cell	Power (kW)	Name
2000	Germany	AFC	7	*Hydra*
2002	Japan	DMFC	30	*Malt's mermaid III*
2002	Germany	PEMFC	160	*DeepC*
2002	Switzerland	PEMFC	300	*Brancec III*
2005	Germany	PEMFC	240	*SiNavy*
2008	Germany	PEMFC	100	*FCS Alsterwasser*
2009	Iceland/Canada	PEMFC	10	*Elding*
2009	Netherlands	PEMFC	70	*Nemo H2*
2009	Singapore/USA	PEMFC	300	*Horizon Fuel Cell*
2009	Norway	MCFC	320	*Viking Lady*
2009	Denmark	DMFC	500	*IRD*
2010	Finland	SOFC	20	*Undine*

It is worth of mentioning that for most of these cases, the power demand required was relatively low compare to the one that is necessary to supply the total auxiliary power demand on board a merchant vessel. The majority of these applications have carried out on river boats, using pure hydrogen as fuel.

2. FUEL CELL TECHNOLOGY

The principle of operation of a Fuel Cell is similar to a battery which will produce energy as long as fuel is supplied**.** According to its internal architecture a Fuel Cell can be divided into two different set of components; the Fuel Cell Stack and the Fuel Cell balance of plant (BoP).

The Fuel Cell Stack, where the electrochemical reaction takes place, consists of a number of cells, each of them form by two electrodes, one anode and one cathode, assembled around an electrolyte. It is on the electrolyte where Oxygen and hydrogen combine generating the electrochemical reaction that produces electricity, water and heat as a result.

The Fuel Cell Balance of Plant is made of the diverse systems that will control the performance of the Fuel Cell Stack. It comprises the thermal management, feed stream, power conditioning and ventilation management system

Different Fuel Cell types are classified according to its electrolyte, at the present time about seven different types exist although this number can be filtered down to three relevant ones if a reasonable power density and fuel flexibility is considered.

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.

Molten Carbonate Fuel Cells (MCFC) operates 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

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

3. AUXILIARY POWER ESTIMATION

The ship auxiliary power demand can be derived by estimating both the total power required and the propulsive power. The total power is estimated using an empirical method that relates the length and speed of the vessel with its cargo deadweight (Kristensen, 2006). The propulsive power demand is obtained by performing a statistical analysis of a ship database, which is filtered to a confidence interval of length and speed of the vessel calculated for the total power required

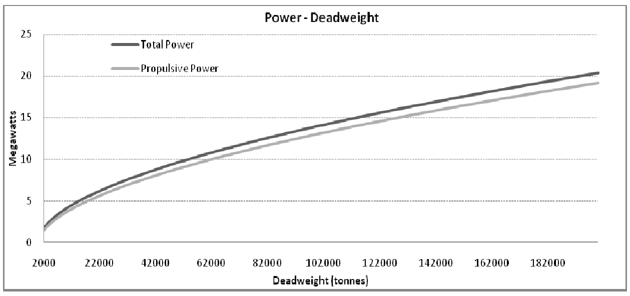

Figure 1: Calculation of Total Power and Propulsive Power for cargo deadweight

The auxiliary power is obtained by subtracting to the total power the propulsive power for a range of cargo deadweight on board a standard merchant ship. The obtained auxiliary power demand is also correlated to an external ship database. This power demand is representative of the operational demand, corresponding to one marine diesel generator.

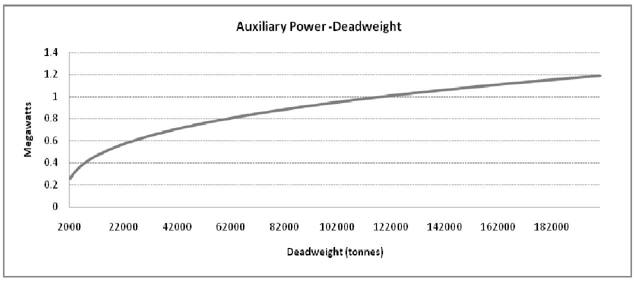

Figure 2: Calculation of Auxiliary Power demand on board

The dimensions and weight of a marine diesel generator are obtained by a statistical analysis of data from industry manufacturers

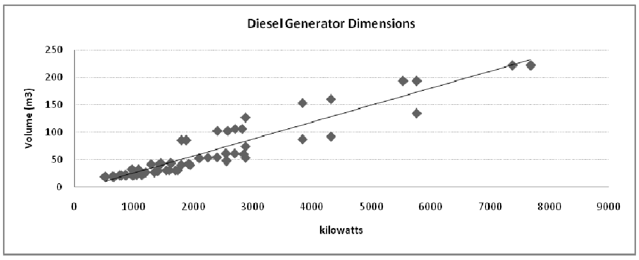

Figure 3: Estimation of the dimensions required for a marine diesel engine generator

The estimated volume of the marine diesel generator can be related to the cargo deadweight through the auxiliary power demand, obtaining as a result, an approximation of the volume required of the ship auxiliary power plant for the range of ship deadweight

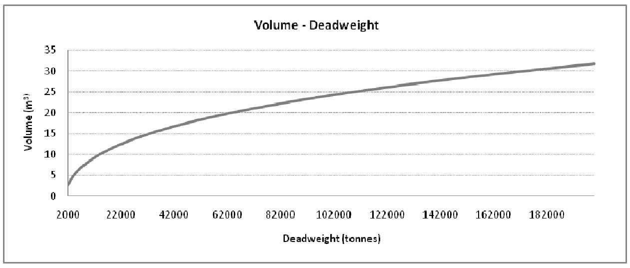

Figure 4: Required volume for a marine diesel engine generator as a function of cargo deadweight

4. FUEL CELL CRITICAL PARAMETERS

As it was mentioned before, due to their high efficiency and low cost and the possibility of integrating them in cogeneration cycles, Solid Oxide Fuel Cells seem to be the most promising solution to replace the combustion engine in the long run.

In order to obtain the design operational parameters of a tubular Solid Oxide fuel cell a detail computational model has been developed. The geometry of the fuel cell is modelled according to some scholars (Dumitrescu et al, 2011). The performance of a Fuel Cell is heavily influenced by external parameters like the operational temperature and the partial fraction of the components of the gas used as fuel. This affects directly the voltage provided by cells in the stack, and hence the power produced.

The model, simulates the performance of a tubular Solid Oxide Fuel Cell fed with rich methane natural gas, in conjunction with a methane steam reactor reformer

4.1 FUEL CELL OPERATIONAL PARAMETERS

The amount of hydrogen required by a single cell, can be related to the current by applying Faraday's law

$$z = \frac{I}{2F} \quad (1)$$

Where, z, represents the molar flow rate of hydrogen and F is the Faradays constant (96485 C/s)

One of the most important operational parameter is the utilization factor, U_f, which accounts for the amount of hydrogen reacted, which is defined as the ration of required hydrogen, and the inlet composition of the feeding gas (Campanari, 2000)

$$U_f = \frac{z}{(H_2+CO+4CH_4)} \quad (2)$$

This factor together with the desired current (A), allow to calculate the amount of methane required

$$CH_4 = \frac{1}{4}(\frac{z}{U_f} - H_2 - CO) \quad (3)$$

Another required parameter, is the steam to carbon ratio, which estimates the amount of steam necessary inside the Fuel Cell stack in order to avoid carbon deposition at the electrodes, damaging the Fuel Cell

$$SCR = \left.\frac{n_{H_2O}}{n_{CH_4}+n_{CO}}\right|_{\text{inlet prereformer}} \quad (4)$$

For a carbon to steam ratio between 2-3 carbon depositions will not take place (Sanchez et al, 2006)

4.2 REFORMING SYSTEM

As well as the Fuel Cell, a detail model must be developed for the steam methane reactor reformer. The performance of both the reactor and the Fuel Cell are directly related. The reactor reformer function is to obtain hydrogen from the natural gas stream. The equation used to model, its performance are described

$$CH_4 + H_2O \leftrightarrow CO + 3H_2 \ (+206.1\ \text{kJ/kmol}) \quad (5)$$

$$CO + H_2O \leftrightarrow CO_2 + H_2 \ (-41.1\ \text{kJ/kmol}) \quad (6)$$

The equilibrium of both reactions is greatly influence by the operational temperature. The hydrogen produced is oxidized producing water, heat and electricity

$$O_2 + 2H_2 \leftrightarrow 2H_2O \ (-241.8\ \text{kJ/kmol}) \quad (7)$$

4.3 VOLTAGE SYSTEM

On the most important parameters to simulate is the Fuel Cell internal voltage, which is a difference between the reversible and irreversible losses on the Fuel Cell (Kambabu, 2007)

$$V_{cell} = E_{cell} - V_{act,cell} - V_{ohm,cell} - V_{conc,cell} \quad (8)$$

Since the cells are connected in series the total voltage output is simply voltage of each of the cells times the number of cells

$$V_{out} = V_{cell}N_{cell} \quad (9)$$

The standard potential, is calculated by using the Nernst equation, which a function of the temperature and the partial pressure of the gases present on the chemical reaction

$$E_{cell} = E_{0,cell} + \frac{RT}{4F}\ln\left[\frac{\left(P_{H_2}^{eff}\right)^2 \left(P_{O_2}^{eff}\right)}{\left(P_{H_2O}^{eff}\right)^2}\right] \quad (10)$$

The irreversible losses, due to the Fuel Cell operation and material properties, are modelled according to (Nehter, 2006), and consist of activation, ohmic and concentration losses.

At low currents, when chemical reaction starts to take place, a voltage loss results due to an energy barrier that must be overcome. This drop is called the *activation voltage drop.* This voltage is calculated by Butler-Volmer equation

$$i = i_0\left\{\exp\left(\beta\frac{zFV_{act}}{RT}\right) - \exp\left(-(1-\beta)\frac{zFV_{act}}{RT}\right)\right\} \quad (11)$$

Due to the fuel cell internal resistance, an *ohmic voltage drop* will appear. This resistance consist mainly of the resistance of the electrodes, electrolyte and the interconnection between cells, and is modelled as, therefore the total voltage drop is the sum of the voltage drop of each of the elements

$$V_{ohm,cell} = V_{anode} + V_{cathode} + V_{electrolyte} + V_{interconnect}$$
(12)

During the reaction process, concentration gradients are formed due to mass diffusion from the flow channels to the reaction sites, decreasing the effective partial pressures. A decrease on the effective partial pressures will also causes a concentration voltage drop on the internal voltage that can be modeled by

$$V_{conc,cell} = \frac{RT}{4F}\left\{\ln\left[\frac{(P_{H_2}^{ch})^2 \cdot P_{O_2}^{ch}}{(P_{H_2O}^{ch})^2}\right] - \ln\left[\frac{(P_{H_2}^{eff})^2 \cdot P_{O_2}^{eff}}{(P_{H_2O}^{eff})^2}\right]\right\}$$
(13)

Using the model the performance of the Fuel Cell and the steam methane reactor reformer are simulated.

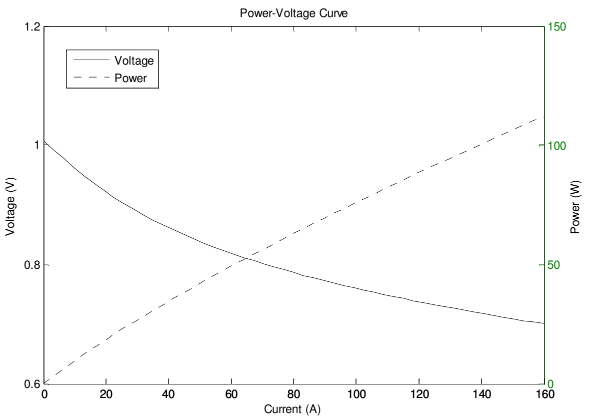

Figure 5: Fuel Cell Voltage and Power curves

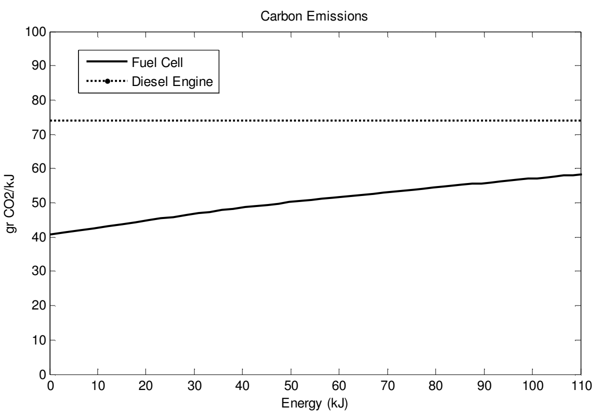

Figure 6: Calculated CO_2 Emissions per energy unit

5. FUEL CELL DIMENSIONS

The Fuel Cell voltage and current are calculated, for a Tubular SOFC fed with rich methane natural gas, and then the power is derived. With these parameters the volume of the Fuel Cell stack can be calculated for the ship deadweight range, and compared to a standard marine auxiliary power generator

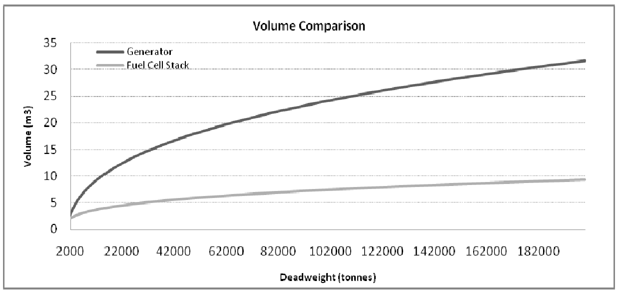

Figure 7: Comparison between Fuel Cell Stack and marine diesel engine dimensions as function of cargo deadweight

It can be seen that the dimensions and weight required for a fuel cell stack in comparison with a marine auxiliary generator are significantly smaller. The total volume required for a Solid Oxide Fuel Cell is estimated based on manufacturer data. As the power demand increases, the auxiliary systems or balance of plant (BoP), become more complex, resulting in a relative increase of the Fuel Cell total volume (Fuel Cell stack plus the Fuel Cell balance of plant).

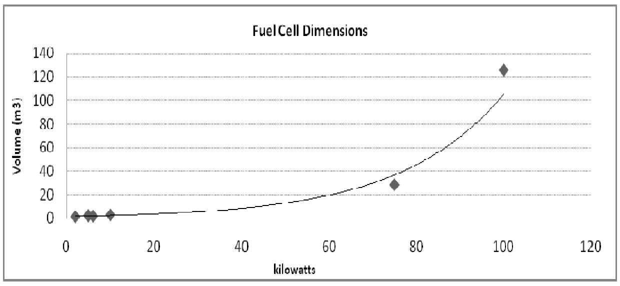

Figure 8: Fuel Cell total dimensions as function of power

The dimensions of the Fuel Cell total volume, Fuel Cell Stack volume and a marine diesel engine generator are directly compared against the power demand. It can be seen that although the Fuel Cell Stack, which is the core of the technology is relatively small, compared to the combustion engine, when taking into account the total dimensions of the Fuel Cell, the resulting volume is significantly larger.

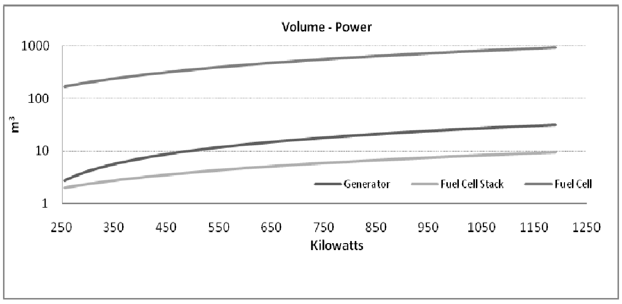

Figure 9: Comparison between Fuel Cell, Fuel Cell Stack and marine diesel engine dimensions

In the hypothetical case that the volume available for the auxiliary power plant is the same as the one required for a marine diesel engine generator install on board, the relatively amount of Fuel Cell Stacks that could be installed, would be about three times more

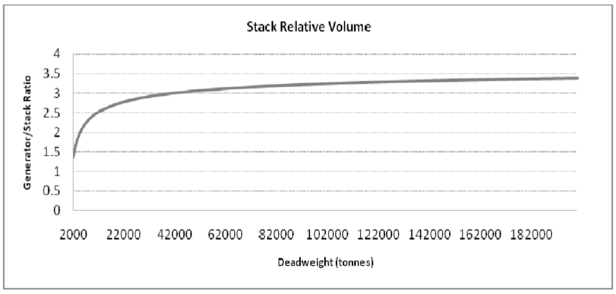

Figure 10: Relative volume of Fuel Cell stack that can be installed for the volume required of a marine diesel engine generator

In the other hand, this value is drastically reduced when taking into account the total volume of the Fuel Cell

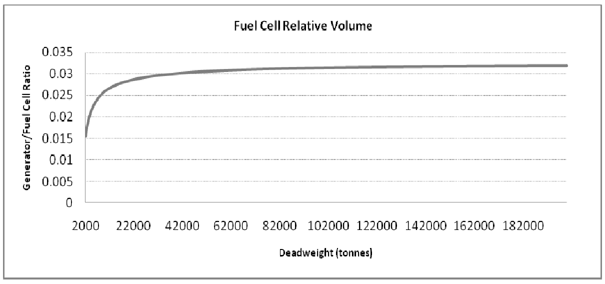

Figure 11: Relative volume of Fuel Cell that can be installed for the volume required of a marine diesel engine generator

The carbon emissions per energy unit compared to a marine diesel engine are relatively lower. The emission factor from the marine diesel engine

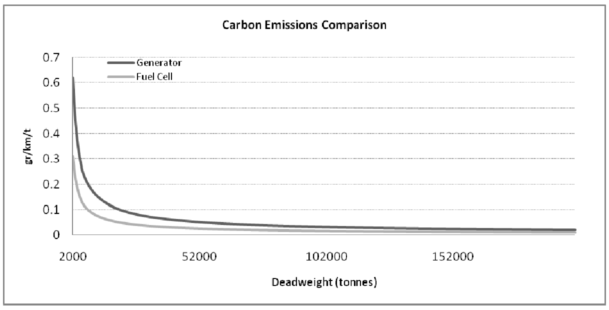

Figure 12: CO_2 emissions comparison between Fuel Cell and marine diesel engine generator as a function of cargo deadweight

6. CONCLUSIONS

Fuel Cells are a very promising alternative to the combustion engine. They have a modular design, fuel flexibility, and high efficiency resulting in potential carbon emission reductions

It must be pointed out, that the majority of the Fuel Cell research and development programs are target towards optimizing the Fuel Cell Stack, both performance and dimensions; this is partially explained due to the fact that the majority of the Fuel Cell applications are being carried out on land-based systems. It has been seen that in the case of a Fuel Cell marine application, one of the biggest problem that should be overcome is the volume required for a high power demand installation. Therefore, in this case, the main point of study should be shifted towards minimizing the balance of plant (BoP) of a high Fuel Cell.
This can directly be achieved by integrating the balance of plant which mainly consist on the thermal energy management system, within the systems on board the ship

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