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Environment-Friendly Inland Shipping

Dynamic modeling of propulsion systems for inland ships using different fuels and fuel cells

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Abstract

To meet possible future emission regulations for inland ships alternative propulsion systems with fuel cell technology and batteries are researched. A rather simple, yet efficient dynamic model is being developed to simulate four different propulsion system configurations with different fuel cells and different fuels. The system configurations and sub models are discussed in this paper, as well as the design considerations and lay-out of the energy control system and results of the first simulations.

Keyword: *Fuel Cell Systems, hydrogen, inland ships, Energy Control System, hybrid propulsion.*

1. Introduction

Is it possible to identify a combination of different fuel cell systems and new energy carriers that is or might become an economic and sustainable alternative for current propulsion systems in inland ships?

It is very likely that in Western Europe more stringent regulations with respect to inland ship emissions will come into effect in the near future. For this reason the possibilities of fuel cell systems for propulsion and energy generation onboard inland ships are investigated. Four different fuel cell (FC) systems have been identified within the research project EFINS (Environment-Friendly INland Shipping). All four system configurations are hybrid propulsion systems, as all configurations include batteries in the system as well.

One aspect of the EFIN shipping research project is to build “simple”, yet efficient dynamic models of these different FC propulsion systems. Input for these simulation models will be power demand measurement data that was logged on an inland ship travelling from Rotterdam harbor to Marl harbor and Geel harbor over the Dutch, German and Belgian waterways. The four different system configurations and the different sub-models that are needed to build four complete dynamic models of the system configurations are the topic of this paper.

The dynamic model of system configuration three, ref. 2.3, has been realized. Results of simulations with this model will be presented in this paper as well.

Fig. 1. Inland tanker on which data was logged.

2. System configurations

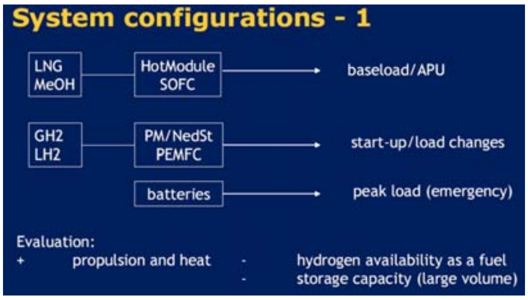
As mentioned in the introduction four different system configurations have been defined in an early stage of the project. In this chapter these system configurations are presented and evaluated.

2.1 Configuration 1: SOFC + PEMFC (multiple fuels)

In this configuration two types of fuel cells are used. Solid Oxide Fuel Cells (SOFC) deliver a certain base load. To do this the SOFC internally reforms LNG (CH_4) or methanol (CH_3OH). Required power during load changes and start-up is provided by Polymer Electrolyte Membrane Fuel Cells (PEMFC) running on liquid hydrogen (LH2) or gaseous, pressurized hydrogen (GH2). Emergency power and power required for peak shaving comes from the battery, which receives its charging power from the fuel cells. A schematic diagram of system configuration 1 is shown in Fig. 2.
An advantage of this system is that it is able to deliver both power (propulsion and auxiliary) and heat. A drawback to this system is that it requires pure hydrogen, which is not readily available as a fuel and requires a large volume for storage, whether it is in liquid or pressurized vapor form.

2.2 Configuration 2: MCFC + PEMFC

The second system configuration also contains a high temperature FC for delivering a base load, a PEMFC for start-up power and load changes and batteries for peak shaving and emergency power. Only in this case the high temperature FC is of the Molten Carbonate Fuel Cell (MCFC) type, which also runs on either LNG or methanol. The fuel for the MCFC in this case also is the fuel for the PEMFC as a fuel reformer is fitted between the fuel tanks and the PEMFC stacks. The fuel reformer reforms LNG or methanol into a hydrogen rich gas, which is fed to the PEMFC. A schematic diagram of system configuration 2 is shown in Fig. 3.
For this system two advantages can be recognized. First this system is also capable of delivering both power and heat and second it does so with a single fuel, whether that is LNG or methanol remains to be seen. Disadvantages of this system are the availability of the fuel reformer, the dimensions of the reformer and certainly the complexity of the reformer.

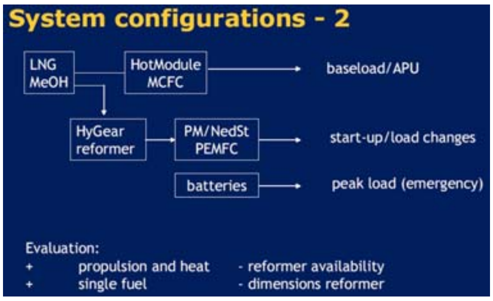


System configurations - 1

LNG
MeOH
HotModule
SOFC
baseload/APU
GH2
LH2
PM/NedSt
PEMFC
start-up/load changes
batteries
peak load (emergency)

Evaluation:
\+ propulsion and heat
\- hydrogen availability as a fuel
\- storage capacity (large volume)

Fig. 2. System 1: SOFC and PEMFC



System configurations - 2

LNG
MeOH
HotModule
MCFC
baseload/APU
HyGear
reformer
PM/NedSt
PEMFC
start-up/load changes
batteries
peak load (emergency)

Evaluation:
\+ propulsion and heat
\+ single fuel
\- reformer availability
\- dimensions reformer

Fig. 3. System 2: MCFC and PEMFC

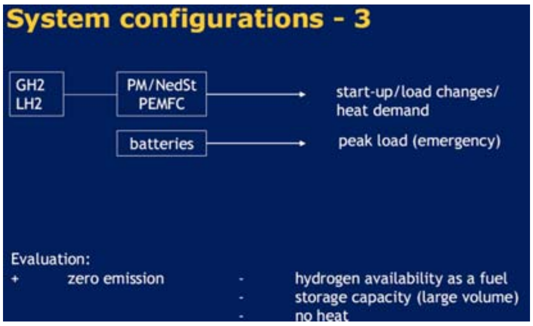
2.3 Configuration 3: All PEMFC

System configuration 3 is the simplest of all configurations. It only contains PEMFC's and a battery. The PEMFC's run on pure hydrogen and deliver all required power. The battery delivers power for peak shaving and in case of emergencies. A schematic diagram of system configuration 3 is shown in Fig. 4.
The biggest advantage of this system is that it has zero (harmful) emissions. Since the fuel contains no carbon at all, there will be no CO_2 emission and the only rest product will be water (H_2O). Of course this does again mean that the poor availability of hydrogen as a fuel and large required storage capacity on board are disadvantages of this system. Also, because no high temperature FC's are present, heat requirements on board can not be delivered by this system.

2.4 Configuration 4: SOFC + PEMFC (single fuel)

The last system configuration that was set is again a combination of SOFC's and PEMFC's, just like the first system configuration. But now the system runs on a single fuel, being either LNG or methanol. With new technology it should be possible to use the exhaust gases of the SOFC as fuel for the PEMFC. The exhaust gases, which were reformed internally, are cleaned after which the hydrogen in the exhaust gases is utilized in PEMFC's. The cleaning stage requires relatively new technology, even in the field of fuel cells which do not have a very long commercial history themselves. It will be interesting to see how such a system will perform, assuming the internal reforming and cleaning stage work well. A schematic diagram of system configuration 4 is shown in Fig. 5.

Advantages of this system are again the fact it produces (propulsion) power and heat, but also that it does so on a single, readily available fuel. Of course the assumption that this system will work as well as hoped may prove wrong in the long run, thus disadvantages are the experimental nature of this system and SOFC technology immatureness.



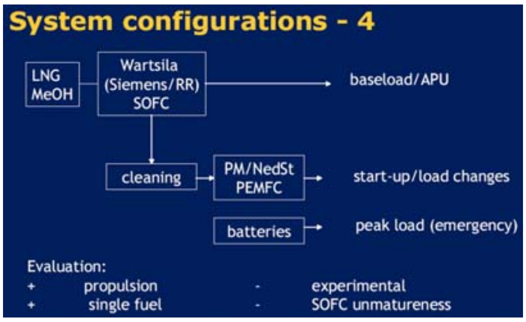
System configurations - 3

GH2
LH2 — PM/NedSt PEMFC → start-up/load changes/ heat demand

batteries → peak load (emergency)

Evaluation:
- \+ zero emission
- \- hydrogen availability as a fuel
- \- storage capacity (large volume)
- \- no heat

Fig. 4. System 3: All PEMFC



System configurations - 4

LNG
MeOH — Wartsila (Siemens/RR) SOFC → baseload/APU

cleaning → PM/NedSt PEMFC → start-up/load changes

batteries → peak load (emergency)

Evaluation:
- \+ propulsion
- \+ single fuel
- \- experimental
- \- SOFC unmatureness

Fig. 5. System 4: SOFC + PEMFC

3. Fuel Cell model

The fuel cell model had to comply with a number of requirements. First of all the model should be accurate of course, yet at the same time it should not be too detailed, as incorporating small effects would not add much to accuracy but would require a lot of computational power. Seeing as the fuel cell model is only a sub model of a larger model, this should not be the case. Next to that the model also needed to be easily adaptable to simulate a PEMFC, MCFC or SOFC as all three types are used in the defined system configurations.

For these reasons a relatively simple and general model is used to calculate the output voltage of the fuel cells from the required current. The model used for that is not dynamic, but just an algebraic equation. To incorporate the dynamic response of the different kinds of fuel cells, a rate limiter was introduced in the models. This rate limiter ensures that the delivered electrical current, which is an output of the fuel cell model, can only increase or decrease with a certain amount of current per time unit [A/s]. The values for this so-called fuel cell current rate, are different for each type of fuel cell and came from a partner in the project who has experience with these values.

3.1 Algebraic model for voltage of fuel cell

The static, algebraic equation (eq. (1)) that is used was derived from [1] and [2]. It gives the fuel cell operating voltage as a function of the fuel cell current density and open circuit voltage:

$$V = E - i \cdot ASR - A_A \cdot ln\left(\frac{i+i_n}{i_{0\_A}}\right) - A_C \cdot ln\left(\frac{i+i_n}{i_{0\_C}}\right) + B \cdot ln\left(1 - \frac{i+i_n}{i_l}\right) \qquad (1)$$

The open circuit voltage E is defined numerically for each fuel cell type in the initialization stage of the model. The same applies to all other parameters in the above equation, except for the current density i, which changes with time in the model. All parameter values are shown in Table 1, as well as the operating temperature and the electrode area A of the fuel cells. These parameter values were fitted to manufacturer data, values found in [1] and [2] and data from experience of the partners. The current density is derived from the required power, which is the input for the overall model. The required power is based on torque and speed measurements that were taken on board a typical inland tanker sailing typical trips from Rotterdam harbor to inland harbors in Germany and Belgium.

3.2 Rate limiter for dynamic model

To account for the dynamic response of the different fuel cell types a rate limiter has been built into to the model. The required current, which is calculated from the measured propulsion power, is fed to this rate limiter, which outputs the same current as long as it is not increasing or decreasing too fast. Should this be the case, for instance during acceleration of the ship, the increase in current is limited. This means that in such a case the power that is delivered by the fuel cell stacks is not equal to the required power. Thus the remaining power needed for the acceleration has to come from somewhere else: the battery.

	PEMFC	MCFC	SOFC
T [K]	353	923	1123
E [V]	1.22	1.08	1.06
A [m^2]	0.029	0.8	0.0144
i_n [A/m^2]	70	70	70
ASR [$\Omega \cdot m^2$]	$1 \cdot 10^{-6}$	$3 \cdot 10^{-6}$	$4 \cdot 10^{-6}$
A_A [V]	0.03	0.03	0.03
$i_{0\ A}$ [A/m^2]	1000	2000	5000
A_C [V]	0.05	0.04	0.04
$i_{0\ C}$ [A/m^2]	1	100	100
B [V]	0.1	0.1	0.1
i_l [A/m^2]	12000	3500	15000
I_rate [A/s]	10	0.06	0.05

Table 1 Equation (1) parameter values for different kinds of fuel cells.

4. Battery model

Basically the battery model (NiMH) has the same function as the fuel cell model; it gives the operational voltage of the battery as a function of the current. However, not only the current has an effect on the operational voltage, the Depth of Discharge (DoD), which is related to the State of Charge (SoC), is important as well. These two variables are used in the model to find the operational voltage using a two dimensional look-up table containing manufacturer data. In fact instead of the actual current the charge rate is used, which is a function of the actual current and the rated capacity of the battery pack:

$$CC = \frac{I_{bat}}{C_{Rat,BP}} \tag{2}$$

The DoD model is based on Peukert's equation and the charge removed (CR) or supplied (CS):

$$C_{peukert} = \left(I_{rated}\right)^k \cdot T_{rated} \tag{3}$$

$$discharging:\ \delta CR = \frac{\left(I_{actual}\right)^k}{3600} \cdot \delta t \ \ /\ \ charging:\ \delta CS = \frac{I_{actual}}{3600} \cdot \delta t \tag{4}$$

$$discharging:\ \Delta DoD = \frac{\delta CR}{C_{peukert}} \ \ /\ \ charging:\ \Delta DoD = \frac{\delta CS}{C_{peukert}} \tag{5}$$

Together with an initial SoC, the changes in DoD provide the DoD at every time step. That DoD together with the charge rate CC results in the operational voltage via the 2D look-up table.

5. Energy Control System (ECS) model

Of course the flow of energy has to be controlled in such a way that the required power is always delivered without exceeding any limits that the involved system components may have. Furthermore the energy control system should be set such that under all conditions the best fuel efficiency is obtained.

The energy control system is divided in a Power Management System (PMS), a Battery Management System (BMS), a Load Management System (LMS) and a Model Predictive Controller (MPC). The latter two have been left out of the ECS for now, but represent possible future development of the ECS.

5.1 PMS

The Power Management System has two important functions:

- Decide on basis of the required power if and when fuel cell stacks are switched on or off and alter the fuel flow accordingly.
- Decide on basis of the SoC of the battery and the dynamics of power demand if and when the battery is charged or discharged.

The required power is divided over the available fuel cell stacks, which should be loaded in their optimal operational range. If the required power forces the stacks to be loaded less than optimal, the PMS can either choose to increase or decrease power flowing to the battery, i.e. charging or discharging, or choose to switch on or off an extra fuel cell stack. Whether the battery is charged or discharged by the fuel cell stacks also depends on the SoC, which should be kept between 50% and 80%, and whether the fuel cell stacks are able to keep up with power demand increase, for instance during acceleration. If this is not the case a part of the required power should also come from the battery.

5.2 BMS

The Battery Management System decides the maximum current that can be drawn or supplied to the battery on basis of the SoC and whether the battery is being charged or discharged. In this way the BMS protects the battery from misuse and lengthens the battery life.

5.3 LMS and MPC

Load Management is not applied in the current model, but should eventually be applied, as it would decide which loads can be switched of on moments that there is not enough power available. A Model Predictive Controller should be applied in a real application to have feed forward information about the power demand, so the PMS can make decisions on basis of probable future power demand, instead of power demand on that moment. This is for instance very practical when a lock is about to be passed. If the PMS would know this in advance it can decide to charge the battery so the lock can be passed on the battery alone.

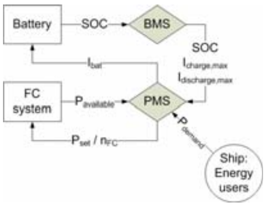


Fig. 6. Information flow diagram of ECS.

6. Results configuration 3

A test environment has been built to check the fuel cell model independent from the overall model. Underneath (Fig. 7) the fuel cell characteristics are shown that are obtained by running this test model.

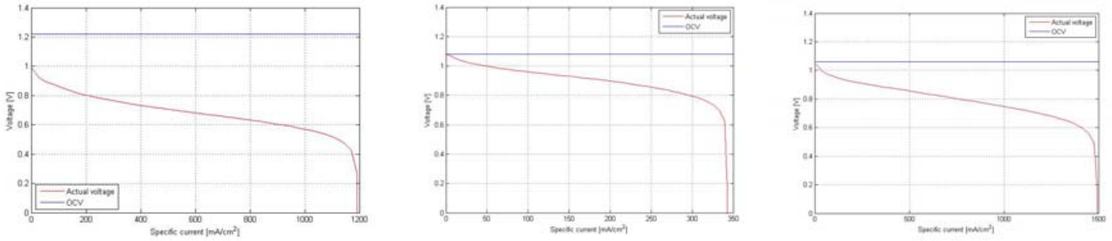


Fig. 7. Fuel cell characteristics for PEMFC, MCFC and SOFC respectively.

For system configuration 3 the overall model has been completed, with a simple PMS and BMS sub model though, which leaves room for improvement. But even with the simple sub model the graph underneath (Fig. 8) is obtained showing that the supplied power follows the demanded power. From this we can conclude that the dynamic response of PEMFC's is sufficient to be applied in inland ships and little battery capacity is needed.

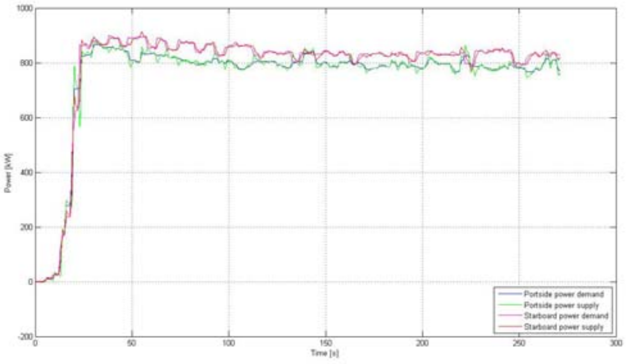


Fig. 8. Power supply and demand during acceleration.

7. Conclusions and further development

A dynamic model simulating a fuel cell and battery based propulsion system for inland ships has been described. Important requirements set for the model were flexibility and high speed. Since it is indeed easy to switch between fuel cell types and realistic fuel cell characteristics are obtained within a few seconds it can be concluded that the fuel cell model meets the requirements. The PMS and BMS sub model can and should be further improved, but from the power demand and supply graph shown in the previous section it can be concluded that even with a relative simple PMS and BMS sub model, the overall model is working quite well. Next to improving the PMS and BMS sub models, further improvements include building other models using the current sub models to simulate the other system configurations. The simulations of the other configurations will be done multiple times, using different values for battery capacity installed in order to optimize this value.

8. Acknowledgements

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