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Preliminary Investigation of a Multi-MW Solid Oxide Fuel Cell Power Plant to be Installed on Board a Cruise Ship

Roberta Russo[a]*, Tommaso Coppola[a], Luca Micoli[a], Andrea Pietra[b]

[a]University of Naples Federico II, Department of Industrial Engineering
[b]Fincantieri group S.p.a
roberta.russo5@unina.it

As the use of both clean energy technologies and alternative fuels in the maritime sector is spreading, studies dealing with the installation of multi-MW power generation plants on board ships have been increasing. Considering this, the present work proposes a 12 MW Solid Oxide Fuel Cell (SOFC) to be installed on board a cruise ship of about 175000 gross tonnes, 345 m length, and powered by Liquefied Natural Gas (LNG). It is supposed that the SOFC generates electrical energy and provides part of the thermal power demand by integrating a heat recovery system. A zero-dimensional (0D) Aspen Plus model has been developed to optimize the onboard layout and to predict the performance of the integrated power plant. Specific parameters, such as the fuel utilisation factor, the pre-heated air temperature, the anodic recycle flow rate, and the exhaust gas temperature, have been manipulated to evaluate the overall efficiency of the integrated power plant under different operating conditions. The model has been validated by comparing the results obtained with data from literature and commercial SOFC modules. A layout configuration of the SOFC plant is suggested and the performances are investigated by varying the efficiency in the range of 60-40%.

1. Introduction

With ever-increasing attention to the issue of sustainability in the maritime shipping sector, it is increasingly necessary to introduce important technological changes to reduce emissions and the impact they generate on the environment (Ampah et al., 2021). Starting from 1st January 2023, new and supplementary regulations became effective to optimize the efficiency of ships and encourage the introduction of alternative fuels to reduce the carbon footprint and the overall impact of the sector (Joung et al., 2020).

Favouring compliance with environmental regulations, in line with more sustainable development in the shipping industry, Fuel Cell (FC) power generation is a technology that shows great potential in eliminating harmful emissions (e.g. NO_X, SO_X, and particulate matter), and in the reduction of CO_2 emissions, especially when compared with emissions from diesel engines (Altosole et al., 2022). A FC power pack consists of a fuel and oxidant processing system and a stack of single FCs that convert the chemical energy of the fuel to electric power through electrochemical reaction (Abdelkareem et al., 2021). There are different types of FC technology, mainly classified according to their operating temperature and electrolyte materials (Sazali et al., 2020). Smaller and medium power applications may favor low and medium temperature FC technologies, such as Proton Exchange Membrane FC (PEM) and high-temperature PEM FC. Larger application which can more easily accommodate waste heat solutions, such as industrial and large maritime, are more suitable for the high temperature technologies such as Solid Oxide FCs. The deployment of FCs fueled with low-carbon fuels (e.g. Natural Gas, NG) or green fuels will also bring local and regional benefits as both emissions and noise are drastically reduced (Kumar Singla et al., n.d.).

A SOFC operates at temperatures between 500-1000°C having an electrolyte based on porous ceramic material, the most commonly used being yttrium-stabilized zirconia. The anode is generally made of a nickel alloy, while the cathode is normally made of lanthanum strontium manganite.

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The feature that makes the SOFC a very attractive technology for the maritime sector, where the introduction of different alternative fuels represents a challenge, is the flexibility of fuel supply. In fact, SOFCs are independent of the hydrogen supply chain and related challenges, and can be fed with NG, light hydrocarbon mixtures, alcohols, and biogas. Fuels are converted into a hydrogen-rich stream through external or internal reforming and CO_2-shift reactions, favoured by the internal thermodynamic condition (*IMO's Work to Cut GHG Emissions from Ships*, n.d.). The resulting process gas is a stream of H_2, CO, CO_2, H_2O, N_2 and CH_4 in different proportions depending on the primary mixture treated and the operating conditions. SOFCs also electrochemically convert carbon monoxide (CO), thus contributing to energy production (Baldi et al., 2020).
SOFCs generally have energy efficiencies of up to 60% which can be further increased when combined with Heat Recovery Systems (HRS), thus saving additional fuel (Al-Hamed & Dincer, 2021).
Considering the overall benefits that could derive from a SOFC power plant on board a ship, this study considers a multi-MW power plant based on this technology to be installed on board a cruise ship to supply the hotel loads and part of the thermal loads by integrating an HRS. As a case of study, a large cruise ship of the latest generation powered by LNG of about 175000 gross tonnes and 345 m length was considered. The study aims to optimize the onboard integrated system layout and evaluate its performance by using a 0D Aspen Plus model. A preliminary investigation on the impact of such a system on the global footprint of the ship is also conducted.

2. SOFC model

There are different SOFC stack technologies and plant designs depending on materials' components, power size, specific application, and SOFC producer (Ellamla et al., 2015). In this work, it has been assumed to model a planar SOFC operating at about 900 °C with an anode gas recirculation, which is one of the most used technologies for nominal power of the order of hundreds of kW (Cigolotti et al., 2021).
Since in Aspen Plus there is no built-in model that can represent the SOFC stack, each of its components has been considered as a separate unit and modelled using the unit operation blocks provided with the software. The thermodynamics and reaction kinetics of each block has been implemented according to the literature data. Each block incorporates complex phenomena like chemical, equilibrium, and electrochemical reactions, and heat and mass transfers, which allow the investigation of single SOFC cell performances, losses, etc. Models of this type are still generally difficult and time-consuming to develop and use as they require the definition of several parameters related to both the materials used and the stack geometry, which are often not declared by SOFC manufacturers. However, this investigation does not achieve the objectives of the present work, which instead focuses on optimizing the layout of the multi-MW SOFC power plant on board the cruise ship to be integrated with an HRS (Rokni, 2010); therefore, the 0D model has been developed for the preliminary calculation of mass and heat flows (Martins, 2022). The flowsheet of the SOFC plant is shown in Figure 1 while Table 1 lists the acronyms and the Aspen Plus unit operation blocks used with a brief description.

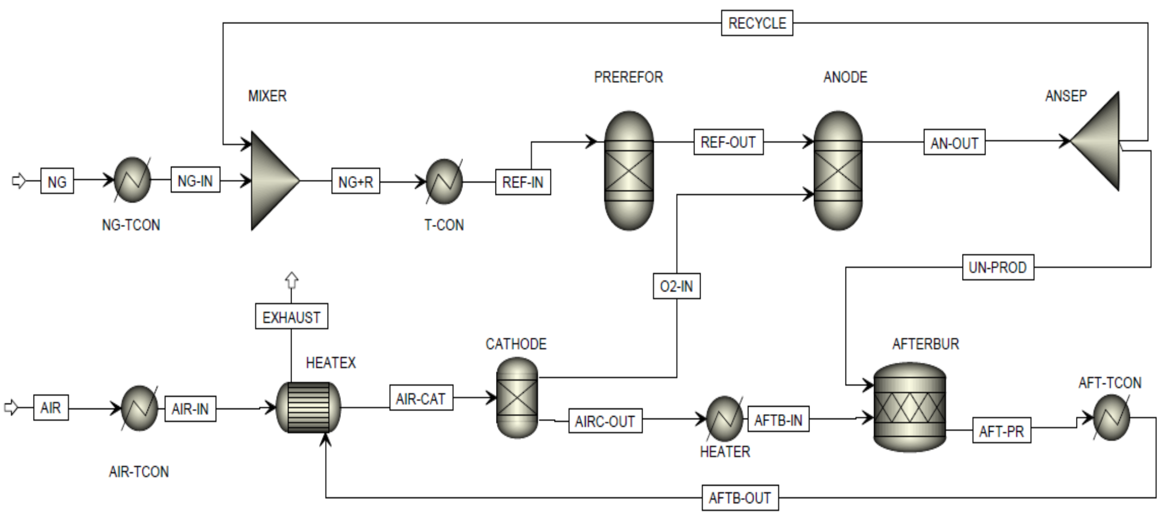

Figure 1: SOFC power generator system flowsheet built-in in Aspen Plus.

Table 1: Description of Aspen Plus unit operation blocks of the flowsheet presented in Figure 1.

Block ID	Aspen Plus unit block	Description
NG-TCON	Heater	Sets the fuel inlet temperature
MIXER	Mixer	Mixes of the recycled unconverted fuel with fresh fuel
T-CON	Heater	Preheats the inlet stream to the reformer reactor up to 850 °C
PREREFOR	RGibbs (Gibbs free energy reactor)	Simulates steam reforming of CH_4 of lighter hydrocarbons and the shifting of CO to H_2 (Water Gas Shift reaction)
ANODE	RGibbs (Gibbs free energy reactor)	Simulates the reforming and electrochemical reactions occurring at the anode
ANSEP	FSplit (Splitter)	Splits the anode outlet into a recycle stream and a stream sent to the afterburner
AFTERBUR	RStoic (Stoichiometric reactor)	Simulates the complete combustion of the remaining fuel with the depleted oxidant
AFT-TCON	Heater	Manages the overall heat balance
HEATER	Heater	Sets the cathode temperature at 900 °C
CATHODE	Sep (Separator)	Simulates the cathode and the electrolyte ion flow separating the O_2 required by the electrochemical reactions from the air inlet stream
HEATEX	HeatX (Heat exchanger)	Preheats the inlet air using the hot gases from the afterburner
AIR-TCON	Heater	Sets the air inlet temperature

The evaporated LNG (CH_4: 90 % vol; C_2H_6: 8% vol; C_3H_8: 2% vol) is fed to the plant at the constant temperature of 20°C and then mixed with the hot unconverted products coming from the anode section. The mixture is sent to an external reforming reactor (pre-reformer) operating at about 850 °C which partially converts methane, light hydrocarbons contained in the LNG, and steam mainly into hydrogen, carbon monoxide, and carbon dioxide. Products from the pre-reformer are fuelled to the anode section where the electrochemical oxidation and the reforming reactions take place, assuming that all the reactions reach the chemical equilibrium. The anode outlet is split into a recycle stream and a stream sent to the afterburner. The anode recycle is at about 900 °C and provides the steam and heat required for the endothermic reforming reactions occurring in the pre-reformer. The recycle flow rate depends on the steam-to-carbon ratio to avoid carbon deposition on the catalyst surface (Doherty et al., 2015). The presence of the afterburner allows the complete combustion of the remaining fuel from the anode with the depleted oxidant and provides the heat required to maintain the stack components at 900 °C. A heat exchanger is used to pre-heat the air inlet using hot exhaust gases from the afterburner.
The generated power and voltage depend on the fuel consumption, SOFC efficiency, etc. which are calculated by applying the widely known equations taken from the literature (Winkler, 2016).
This model can be adapted to different SOFC power sizes. In the present work, to better manage the load variations, a plant composed of multiple 300 kW modules (each made up of 4 x 75 kW SOFC stacks) was considered. Each basic module has a footprint of about 1.1 x 1.3 x 2.1 m (D x W x H), a weight of about 1.8 t, and integrates all the required auxiliaries (BoP – Balance of Plant) (McPhail et al., 2022).

3. Results

3.1 Model validation

The model was validated using data from literature and those available from some commercial products based on 20 - 100 kW SOFC stacks and plants powered by natural gas. Specifically, the calculated exhaust temperature (T_{EX}) and available thermal power were compared with literature data. It was considered that T_{EX} is affected by the air flow rate, which varies considering an O_2 inlet / O_2 stoichiometric ratio in the range of 3.5 - 5.5 depending on the considered SOFC technology and the overall heat balance. It resulted that the calculated T_{EX} varies in the range of about 280 – 350 °C and decreases as the air flow increases; this temperature range is in agreement with literature data (Doherty et al., 2010, 2015). To simplify the calculation, steady-state and isothermal conditions have been considered and all the pressure drops have been neglected.

3.2 Simulation results

Multiple sensitivity analyses were conducted to evaluate the optimal values of some SOFC stack's parameters; due to the limited space available for the text, it is preferred to report only the optimal calculated values, which are shown in Table 2.
These values are similar to those presented in other works (Pourrahmani et al., 2022). Then, assuming 60% electric efficiency and steady-state condition, the specifications of each stream of the SOFC model (refer to

Figure 1) can be calculated and reported in Table 3. It should be noted that the fuel utilization factor refers to hydrogen electrochemically reacting to produce the electric power compared to the stoichiometric one that could be obtained from the LNG through the reforming reactions. It is assumed that CO is shifted to H_2 and only H_2 reacts electrochemically.

Table 2: SOFC stack parameters.

Parameters	Value
Anodic recycle ratio (%)	85
Fuel utilization factor (%)	67
Molar feed ratio (mol_{AIR}/mol_{LNG})	23
Pre-heated air temperature (°C)	650

Table 3: Main specifications of each stream of the proposed SOFC model.

Stream	Mass Flow [kg/h]	T [°C]	Composition [mol fraction]							
			H_2	O_2	CH_4	CO	N_2	H_2O	C_2H_6	C_3H_8	CO_2
AFT-PR	338.9	1183	0	0.10	0	0	0.75	0.10	0	0	0.05
AFTB-IN	300.6	850	0	0.13	0	0	0.85	0.02	0	0	0
AFTB-OUT	339.0	850	0	0.10	0	0	0.75	0.10	0	0	0.05
AIR	330.2	20	0	0.20	0	0	0.80	0.02	0	0	0
AIR-CAT	330.2	650	0	0.20	0	0	0.80	0.02	0	0	0
AIR-IN	330.2	25	0	0.20	0	0	0.80	0.02	0	0	0
AIRC-OUT	330.6	650	0	0.13	0	0	0.85	0.02	0	0	0
AN-OUT	255.7	850	0.13	0.08	0	0.21	0	0.48	0	0	0.10
EXHAUST	399.0	303	0	0.10	0	0	0.75	0.10	0	0	0.05
NG	8.8	20	0	0	0.90	0	0	0	0.08	0.02	0
NG+R	226.2	791	0.12	0.07	0.04	0.20	0	0.45	0	0	0.10
NG-IN	8.8	25	0	0	0.90	0	0	0	0.08	0.02	0
O2-IN	29.5	650	0	1.00	0	0	0	0	0	0	0
RECYCLE	217.4	850	0.13	0.08	0	0.21	0	0.48	0	0	0.11
REF-IN	226.2	850	0.12	0.07	0.04	0.20	0	0.45	0	0	0.10
REF-OUT	226.2	850	0.16	0	0	0.21	0	0.50	0	0	0.14
UN-PROD	38.4	850	0.13	0.08	0	0.21	0	0.48	0	0	0.11

3.3 Plant performance

The performance of a 12 MW SOFC power plant was investigated by considering the stack efficiency value at 60, 50 and 40%. An efficiency reduction is expected due to ageing. Most relevant results are reported in Table 4.

Table 4: Specifics of the main streams.

Stream		Temperature [°C]			Mass Flow [t/h]		
	η	0.60	0.50	0.40	0.60	0.50	0.40
NG		20	20	20	1.4	1.8	1.6
AIR		20	20	20	52.8	108.6	45.9
EXHAUST		303	284	316	54.2	110.4	47.5

As expected, the reduction in efficiency affects the T_{EX}, fuel consumption, airflow, and produced power. The highest efficiency value (60 %) results in the lowest fuel consumption (1.4 t/h) producing exhaust at about 303 °C. If the efficiency is at 50 %, as the fuel consumption increases (1.8 t/h), the generated heat increases, and the airflow increases accordingly (almost doubled), thus resulting in a higher thermal power available in the exhaust for heat recovery, even though T_{EX} is slightly lower (284 °C). In this condition, the nominal power is still guaranteed (12 MW). In the case the efficiency is 40%, the resulting power that can be produced by the SOFC plant is about 10.1 MW as part of the fuel is not converted electrochemically but burns catalytically producing overheating; as a result, an increase in the airflow is required to control the overall heat balance, and the fuel flow is reduced as well.

3.4 Onboard layout

Three rooms were identified on board the cruise ship (named FC Room 1, 2 and 3) intended to contain the SOFC modules, with volume and surface area as per Table 5. According to this, to generate 12 MW of electric power, the arrangement of 40 SOFC modules is proposed as shown in Figure 2. The weights and footprints of the SOFC modules in each room are shown in Table 5.

Table 5: Main specifics of the FC rooms on board the cruise ship.

	SOFC					ROOM	
	Module [num]	Power [kW]	Volume [m^3]	Area [m^2]	Weight [t]	Volume [m^3]	Area [m^2]
Room 1	14	4200	270.2	126.3	62.6	1290	300
Room 2	14	4200	270.2	126.3	62.6	1290	300
Room 3	12	3600	231.6	108.2	53.6	780	280

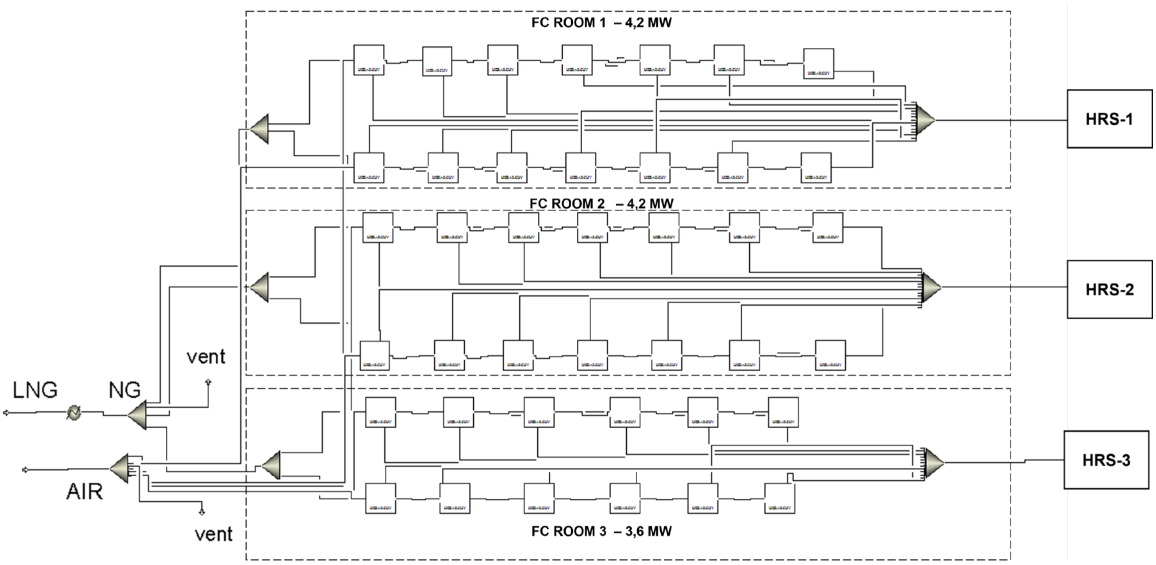

Figure 2 : 12 MW SOFC layout flowsheet built-in in Aspen Plus.

The fuel distribution scheme includes an evaporator for LNG and a separator of the main NG flow into three main streams, which are connected to secondary separators which feed the SOFC modules of the three rooms (in Figure 2). A vent line was also considered to manage overpressures and overloads.
Each separator feeds two separate groups of SOFCs composed of 7 or 6 modules connected in series, where the first module's overload fuel of constitutes the inlet stream of the second one, and so on. The last module of the series has no residual NG. It was verified that this configuration ensures that most of the SOFC modules operate in the optimal supply condition in case of load variations, allowing the lowest LNG consumption (highest efficiency). A similar configuration is also adopted for the distribution of the air streams to the cathodic sections. The exhausts from each module are collected by a mixer and then directed to an HRS, which can both generate steam flows and recover condensed water to be used on board, thus saving further fuel.

4. Conclusions

The installation of a 12 MW SOFC power plant on board an LNG-fuelled cruise ship was considered in order to reduce its global emissions, especially while moored in ports, where it would be beneficial to turn off the dual-fuel engines. The SOFC plant is meant to supply the hotel loads and a part of the thermal loads by integrating a heat recovery system. A zero-dimensional Aspen Plus model was developed to optimize the most relevant SOFC working parameters and predict the SOFC plant performance mainly as a function of the efficiency reduction. The model was also used to suggest a preliminary layout configuration on board the cruise ship. The 12 MW SOFC plant is made of stacks that are grouped in 300 kW modules, located in three different rooms, and integrated with three independent HRSs. Although the 12 MW SOFC plant requires considerably more space than an ICE of the same power, on the other hand, it allows to save fuel and reduces the ship's overall emissions.

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