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MCFC-based marine APU: Comparison between conventional ATR and cracking coupled with SR integrated inside the stack pressurized vessel

S. Bensaid[a], S. Specchia[a,*], F. Federici[b], G. Saracco[a], V. Specchia[a]

[a]Materials Science and Chemical Engineering Department, Politecnico di Torino, Corso Duca degli Abruzzi, 24 - 10129 Torino, Italy
[b]Ansaldo Fuel Cells S.p.A., Corso Perrone 25, 16152 Genova, Italy

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ABSTRACT

In the present work the implementation of MCFCs as auxiliary power units on-board large vessels, such as cruising, passengers or commercial, ships was investigated. The MCFC stack was designed to supply 500 kW_e and was fed with diesel oil undergoing a reforming process. The system modelling of the plant was performed in steady-state and aimed at assessing the power efficiency for different reforming strategies, process configurations and constituting items thermal integrations. The code Matlab/Simulink was used to this end. Two major fuel processing strategies were examined: ‘‘auto-thermal reforming’’ and ‘‘inside vessel steam reforming’’. The latter consisted of a pre-reforming unit in which the liquid fuel underwent a catalytic cracking in mild conditions; subsequently, the resulting gas mixture made of light hydrocarbons was mixed with steam and fed into a steam reformer inside the MCFC stack vessel, where conversion to syngas occurred. Due to the high temperature (650 °C) exothermic level of MCFC, the stack was compatible with a syngas steam reforming production thermally self sustained. This allowed to increase the global electrical efficiency from 32.7% (for the ATR-based system) up to 44.6%. The process was then designed aiming at increasing the overall efficiency by thermally integrating the outlet flue gases with the pre-heating section. This lead to efficiencies equal to 39.1% and 50.6% for the ‘‘auto-thermal reforming’’ and ‘‘inside vessel steam reforming’’, respectively. Finally, the process was upgraded from an auxiliary power unit (APU) to a combined heat and power unit (CHP), since the residual heat in the flue gases was recovered for heating purposes (sanitary water production) and the demineralised water recirculation was implemented to reduce the water make-up and the process environmental footprint.

1. Introduction

A clear trend towards the design and installation of integrated electric propulsion systems in ships has emerged in the last few years [1–3]. Most of the cruise ships employ diesel engines to produce propulsion and diesel based generators for the hotel power for ships, as illustrated in Table 1 [1,4,5] with problems mainly linked with environmental protection: maritime transport accounts for about 3% of global petroleum consumption but contributes 14% of NO_x and 16% of SO_x.

* *Corresponding author*. Tel.: +39 011 0904608; fax: +39 011 0904699.
E-mail address: stefania.specchia@polito.it (S. Specchia).
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Nomenclature

c_p	specific heat capacity at constant pressure, $kJ\,kg^{-1}\,K^{-1}$
c_v	specific heat capacity at constant volume, $kJ\,kg^{-1}\,K^{-1}$
HCR	hydrogen (H) to carbon ratio in the fuel
HHV_{Fuel}	higher heating value of the fuel, $MJ\,kg^{-1}$
k	expansion/compression coefficient
LHV_{H_2}	lower heating value of H_2, $MJ\,kg^{-1}$
LHV_{CO}	lower heating value of CO, $MJ\,kg^{-1}$
LHV_{Fuel}	lower heating value of the fuel, $MJ\,kg^{-1}$
m_{H_2}	H_2 mass flow rate, $kg\,h^{-1}$
m_{CO}	CO mass flow rate, $kg\,h^{-1}$
m_{fuel}	fuel mass flow rate, $kg\,h^{-1}$
MW	fuel molar weight, $kg\,kmol^{-1}$
O_2CR	oxygen (O_2) to carbon ratio
SCR	steam to carbon ratio
ΔH_v	fuel vaporisation enthalpy, $kJ\,kg^{-1}$
η_{convH_2}	conversion to H_2 efficiency of the fuel processor
$\eta_{convTOT}$	conversion to H_2 and CO efficiency of the fuel processor
$\eta_{OVGross}$	gross electrical efficiency of the overall system
η_{OVNet}	net electrical efficiency of the overall system
λ	$O_2/O_{2\ stoichiometric}$ in fuel burners

Other relevant pollutant emissions are particulate matter (PM), VOCs and PCAs. However, CO_2 emissions are relatively low since the thermal efficiency of the engines (or combined cycle turbines) used in large vessels tend to be amongst the highest of all prime movers and of static combined cycle generating plant [6]. Under the spur of national and international committees [7–9], the main naval companies are considering the use of integrated electric plants in future naval ships. The implementation drivers are primarily lower life cycle costs, reduced noxious emissions (in particular PM and NO_x), low vibrations and noise levels. The fuel cells (FCs) offer several advantages over diesels [10–12]: these include higher thermal efficiency; a flat efficiency curve vs load; lower emissions, vibrations and noise. Presently, however, FCs initial costs are significantly higher than for diesels. Hydrogen may offer considerable potential as a marine fuel. Its reduced mass when compared with existing hydrocarbon fuels (the total fuel thermal power being the same) can usefully increase the ship-owner payload; this in turn benefits the economics of oceanic transport and provides the opportunity to compete in new markets [13]. Moreover, the potential to virtually eliminate pollution at the point of use may boost significantly the naval industry considering that exhaust emissions from shipping are becoming a matter of global concern. But the relatively poor volumetric energy density achieved by even the most effective storage options [14,15] can be a limiting factor for ships, particularly for the largest ones. This is particularly the case with high-speed vessels where the fuel load is proportionally greater. Given the existing fuelling infrastructure for marine transports (mainly marine diesel, kerosene and natural gas) and the relatively space restrictions on-board marine vessels, combined fuel reforming and FCs technologies are an attractive option for shipboard power systems (propulsion and/or auxiliary power requirements [16–21]), for future 'Green Ship' applications (see Table 1 [22]). Moreover, they also allow tight integration of multiple thermal sources and heat loads, making them an ideal candidate for combined heat and power (CHP) marine applications [23–27].

Some of the FCs benefits provided to the process industry could also apply in the marine field [1,3–5,14,19,20]. Of special interest is the FCs high efficiency, since it may translate into fuel cost savings. Moreover, FCs efficiency is relatively constant over a broad range of power settings: such

Table 1 – Main characteristics of the major propulsion systems for various maritime transports and requirements of FCs-based APU systems.

	Tourist crafts	Leisure crafts	Offshore support vessels	Research and survey vessels (icebreakers)	Fast ferries	Ferries	Passengers cruise vessels	Coastal cargo vessels	International cargo vessels
Low speed diesel engine								X	X
Medium speed diesel engine			X	X	X	X	X	X	
High-speed diesel engine	X	X	X	X	X				
Simple cycle gas turbine		X	X	X	X		X		
Advanced cycle gas turbine							X		
Mechanical propulsion	X	X	X	X	X	X	X	X	X
Electric propulsion			X	X		X	X		
Fuel cells	X	X	X	X	X	X	X	X	X
FCs-based APU systems	X	X	X	X	X	X	X	X	X