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Exergy analysis and optimisation of a marine molten carbonate fuel cell system in simple and combined cycle configuration

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ABSTRACT

In this paper we present the exergy analysis and design optimisation of an integrated molten carbonate fuel cell (MCFC) system for marine applications, considering waste heat recovery options for additional power production. High temperature fuel cells are attractive solutions for marine energy systems, as they can significantly reduce gaseous emissions, increase efficiency and facilitate the introduction of more environmentally-friendly fuels, like LNG and biofuels. We consider an already installed MCFC system onboard a sea-going vessel, which has many tightly integrated sub-systems and components: fuel delivery and pre-reforming, internal reforming sections, electrochemical conversion, catalytic burner, air supply and high temperature exhaust gas. The high temperature exhaust gasses offer significant potential for heat recovery that can be directed into both covering the system's auxiliary heat requirements and power production. Therefore, an integrated systems approach is employed to accurately identify the true sources of losses in the various components and to optimise the overall system with respect to its energy efficiency, taking into account the various trade-offs and subject to several constraints. Here, we present a four-step approach: a. dynamic process models development of simple and combined-cycle MCFC system; b. MCFC components and system models calibration via onboard MCFC measurements; c. exergy analysis, and d. optimisation of the simple and combined-cycle systems with respect to their exergetic performance. Our methodology is based on the thermofluid and chemical reactions modelling of each component, via our in-house ship machinery systems modelling framework, DNVGL COSSMOS. For the major system components spatially distributed exergy balances are considered in order to capture the coupling of the local process phenomena and exergy destruction with component design characteristics. Exhaust heat recovery is considered using a steam turbine combined-cycle module integrated with the rest of the MCFC system. Both the simple and combined cycle MCFC systems are optimised with respect to their overall exergetic efficiency subject to design, technical, operational and space constraints. The exergy analysis identified and ranked the sources of exergy destruction and the subsequent optimisation yielded significant improvement potential for both systems. The simple MCFC system optimisation yielded an exergy efficiency improvement of 7% with 5% more power produced. Heat recovery in the combined cycle MCFC resulted in 40% more power produced, with a 60% overall exergy efficiency (relative increase of 45%). Both MCFC systems outperform conventional dual-fuel engines with respect to efficiency, having also a positive impact on CO_2 emissions with a relative reduction of about 30%.

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1. Introduction

Molten carbonate fuel cells (MCFC) are attractive solutions for shipboard power generation, due to their high efficiency and high temperature exhaust heat recovery potential. Therefore, they can offer reductions in emissions to air, an increase of the overall system efficiency and facilitate the use of more environmentally-friendly fuels, such as LNG and biofuels [1–3]. These features are becoming increasingly important to modern shipping, since the rapidly varying fuel costs, increased sustainability concerns and existing/forthcoming emissions regulations pressure shipowners to introduce more efficient, cost-effective and environmentally friendly ship energy systems.

The concept examined in this work is based on an already installed MCFC system onboard the platform (offshore) supply vessel Viking Lady (owned by Eidesvik Offshore ASA) operating on the Norwegian continental shelf. The MCFC serves as an auxiliary

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Nomenclature

Latin symbols

A	area, m^2
D_{out}	tube external diameter (Fig. 6), m
FU	fuel utilisation, –
I	current, A
j_C	current density A/m^2
h_{fin}	fin height (Fig. 6), m
L	length, m
$\dot{m}$	mass flow rate, kg/s
N_{cells}	number of cells in a MCFC stack
p	pressure, Pa or bar
P_{tube}	tube pitch (Fig. 6), m
$r_{\varepsilon D}$	relative exergy destruction, –
R_{RC}	cathode exhaust recirculation ratio, –
sp_{fin}	fin spacing (Fig. 6), m
T	temperature, K
t_{fin}	fin thickness (Fig. 6), m
U	voltage, V
V	volume, m^3
$\dot{W}$	power, W or kW
W	width, m

Greek symbols

δ	exergy destruction ratio, –
$\dot{\varepsilon}$	exergy rate, W or kW
$\dot{\varepsilon}_D$	exergy destruction, W or kW
ζ	exergetic efficiency, –
ϕ^S	electrode electric potential, V

Subscripts

a	anode
BL	baseline
CC	combined cycle
c	cathode
ch	channels
HT	heat transfer
HE	heat exchanger
SC	simple cycle
sys	overall system

power unit, with rated power of 320 kW. The design, installation, commissioning and testing of the MCFC system performed during a series of research demonstration projects FellowSHIP I–III [2,4,5], partly funded by the Norwegian Reseach Council. Up to now, this prototype installation has accumulated more than 18,000 h of operation in the past 5 years. This work aims at exploring further this technology, improving further its efficiency, optimising the configuration and exploiting the full potential of the fuel energy input. We present the mathematical modelling, exergetic analysis and design optimisation of a marine MCFC system considering waste heat recovery options for additional power production. This system features many tightly integrated sub-systems and components: fuel delivery and pre-reforming, internal reforming sections, electrochemical conversion, catalytic burner, air supply and high temperature exhaust gas. In addition, the high temperature exhaust gasses offer significant potential for heat recovery that can be directed into both covering the system's auxiliary heat requirements and power production. Therefore, an integrated systems approach using exergy analysis and coupled with design optimisation is particularly appropriate for such complex systems, since it can accurately reveal the true sources of losses (exergy destruction) in the various components and to optimise the overall system with respect to its exergy efficiency, taking into account the various trade-offs and subject to several constraints. Further, the exergy analysis of complex energy conversion processes (electro-chemical, heat exchange, mechanical/electrical work) can alleviate certain shortcomings appearing in traditional energy (first-law) approaches that often fail to capture the overall picture and true sources of losses within complex highly-integrated systems [6–8].

The study builds upon our previous work [9], in which we have applied exergy-based optimisation on the fuel-processing sub-system (steam methane pre-reformer) of the marine MCFC unit. Here, we generalise this approach by applying to the overall system and taking it further by proposing a configuration alternative with waste heat recovery (WHR). In Section 2 the system layout, its components and main functions is presented. Section 3 presents the mathematical modelling of the individual component models and the validation of the overall system. In Section 4 the exergy-based design optimisation problem formulations are given and Section 5 presents the results of the study. Finally, in Section 6 our main concluding points are summarised.

2. System description

We consider the marine MCFC system as shown in Fig. 1. The major components of the system are: a low pressure water evaporator, a steam/natural gas fuel mixer and heater, the external steam–methane pre-reformer (SMR), the direct internal reformer (DIR), the molten carbonate fuel cell (FC), an exhaust gas recirculation valve, a catalytic burner, a gas circulation fan and an air induction fan to the burner. The water evaporator and the steam methane heater are cross flow heat exchangers utilising the hot exhaust gasses of the MCFC stack. The SMR is a reformer of tubular design filled with pellets of catalytic packing material with well insulated near-adiabatic walls. The SMR is used to completely reform the higher-chain hydrocarbons present in the natural gas feed as well as to partly reform methane to hydrogen in order to create the suitable operating conditions for the internal DIR [5,9].

The MCFC stack consists of multiple cells of alternating DIR and electrochemical fuel cell elements. The pre-reformed fuel is completely reformed to hydrogen in the DIR and then electrochemical reactions occur in each of the fuel cell elements. The DIR reformed fuel gas is led to the anode gas channels of the fuel cell, while the cathode gas channels are fed from the exhaust gasses of the catalytic burner via a circulation fan. A part of the hot exhaust gasses in the cathode outlet are recirculated to the catalytic burner, while the rest are released out of the stack to the fuel pre-processing components and finally, to the atmosphere. In addition, fresh air is supplied to the catalytic burner via an air induction fan. The catalytic burner consists of the catalyst section, where combustion takes place, and a reversal plenum (chamber) that hot exhaust gasses are expanded to ensure uniform pressure conditions at the circulation fan inlet. The detailed description of this configuration can be found in [5,10].

The main function of the marine MCFC system is to serve as an auxiliary power unit, covering base electrical loads of the vessel [5]. This entails near-constant operation close to its nominal load point. Therefore, the system optimisation, presented in Section 4,

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