Thermodynamic analysis for SOFC/ICE integration in hybrid systems for maritime application

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Abstract. As the International Maritime Organization has set 2030 and 2050 targets to reduce the environmental impact of the maritime sector, it is mandatory to investigate innovative solutions aimed at fuel saving and reduction of ship emissions. In this paper, the integration of Solid Oxide Fuel Cells (SOFC) and Internal Combustion Engine (ICE) is investigated for maritime application, targeting a short-sea ferry as a case study operated by a marine gas engine (MGE) rated 750 kW. The paper aims to model via an in-house tool (WTEMP) the proposed hybrid system and study thermodynamic interaction among the two main energy systems, SOFC and ICE, considering blending anode-off gas from the SOFC with natural gas in the ICE. The results showed relevant efficiency enhancement and fuel/CO_2 emission savings if compared with traditional MGE while the main source of exergy loss of the hybrid system is ICE.

1 Introduction

In order to tackle climate change issues, all sectors causing anthropogenic Greenhouse Gas (GHG) emissions have to reduce their environmental impact. Concerning the maritime sector, responsible today for nearly 3% of global CO_2 emissions (1 Gton/year), the International Maritime Organization (IMO) published in 2018 a long-term strategy targeting to cut 40% of CO_2 emissions per transport work by 2030, pursuing efforts towards 70% by 2050 [1]. To reach this target, many measures can be adopted in different time horizons, including vessel optimization, speed reduction, voyage optimization, and the use of alternative fuels and/or propulsion technologies [2–5]. In particular, the latest two have been investigated in recent literature by many authors, as they have the potential to cut emissions in the most significant way [6,7], although some of the alternative solutions are not ready on the market yet. The use of fuel cells has been proposed, since their potential in terms of high efficiency, low noise, and vibrations, and use of clean fuels [8,9]. Proton Exchange Membrane Fuel Cells (PEMFC) and Solid Oxide Fuel Cells (SOFC) are the most promising ones, as reported in many research works [7,10]. Compared to PEMFC, SOFC have the advantage of fuel flexibility, they can be fed by many fuels, i.e. natural gas [11], methanol

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[12], and biogas [13]; furthermore, thanks to their high operating temperatures, i.e. 800-1000 °C, they can be employed in hybrid systems with micro gas turbines [14] or internal combustion engines [15]. Despite their higher efficiency, SOFCs gained interest more for hotelling/on-board services than propulsion systems (where PEMFCs are more attractive) due to their lower power capacity. Moreover, the possibility of SOFC hybridization is desirable because a hybrid system could enhance the efficiency of the propulsion system (once SOFC and ICE operate together) and on the other side guarantee that the SOFC could be used during hotelling or harbor operations.

2 SOFC / ICE hybrid system configuration

The layout of the SOFC/ICE hybrid system is introduced in Figure 1. As known, the SOFC's operation depends on reformed fuel to produce electrical energy; therefore, an external pre-reformer is present in the system. The reformed fuel enters the anode side of the SOFC, reacts with the air from the cathode side to generate electricity, and leaves the SOFC in the form of anode-off gas (AOG).

There are two heat exchangers in the proposed system (H.E1, H.E2) to pre-heat methane and air, respectively by using the AOG and cathode air out of the SOFC. The AOG is split into two stream flows (A2 and A3) for superheating the steam in the superheater (S.H2) and preheating the fuel in H.E1. Then, A1 and A2 stream flows are mixed again in a flow mixer (F.M1) and circulated in a gas/water separator to remove the water vapor from the AOG. Therefore, the composition of AOG after the separator contains hydrogen, carbon monoxide, and carbon dioxide. The proposed system is based on blending the AOG with natural gas (NG) to be used as an energy source in ICE to enhance efficiency and performance. The quantity of AOG circulated into the flow mixer (F.M2) to be blended with NG is controlled by using a flow separator (F.S2) to stabilize AOG-NG blend volumetric percentages to be 30-70 %. The combustion in ICE produces mechanical energy that can be converted to electrical energy by using an alternator. The exhaust gas from ICE is used to generate the steam required for the reforming of CH_4 via a heat recovery steam generator (HRSG).

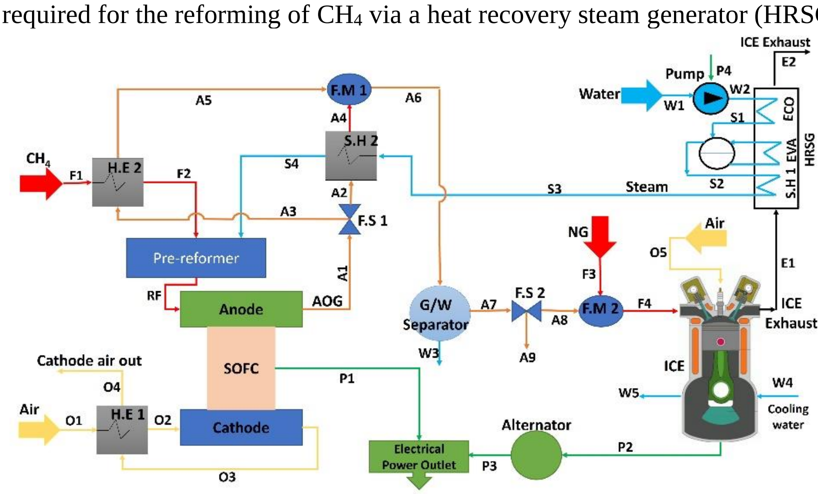

Fig. 1. System layout of the proposed integration between SOFC and ICE

The analysis is performed using the in-house WTEMP (Web-based Thermoeconomic Modular Program) software for energy, exergy, and economic design point analysis, developed in the last twenty years by the Thermochemical Power Group (TPG) at University of Genoa and already used to model advanced energy systems also based on fuel cells [16–18]. WTEMP adopts a modular approach and a standard component interface, which allows the user to build complex cycle configurations in a short time, also allowing the user to easily add new components without modifying the core of the software. Each component is described by three subroutines, which define its thermodynamic, exergy, and thermo-economic properties at the design point.

The model is used to simulate the hybrid system at different load sharing between SOFC and ICE to analyze the system performance via the current key points: system efficiency, fuel consumption, and CO_2 emissions. The hybrid system is proposed to generate 750 kW as net electrical power (net power output is a constraint of the simulation while designing the system) which can be used as a propulsion system onboard a small ferry ship. In the present study, pure methane is proposed to be the main fuel of SOFC and blend AOG with NG to power the ICE as presented in Figure 1. The main input parameters of the thermodynamic model are stated in Table 1 and considering the ambient ISO conditions are the reference state conditions. Furthermore, the pressure and temperature of NG at its inlet flux are 2.4 bar, and 27 °C, respectively. To check the robustness of the WTEMP model, it was verified with previous research [19] that studied the hybridization of SOFC and ICE through numerical and experimental studies.

Table 1. Input parameters for the thermodynamic model

Component	Parameter	Value
SOFC	Current density [A/m^2]	5000
	Fuel utilization [%]	80
	Fuel cell temperature [°C]	870
Reformer	Conversion ratio [%]	10
	Steam to Carbon ratio	2
	Operating temperature [°C]	800
ICE	Air/fuel ratio	10.7
	Mechanical efficiency [%]	85
Heat exchangers	Efficiency [%]	85
	Pressure drop [bar]	0.01
Pump	Adiabatic Efficiency (%)	83

The performance of the integration between the SOFC and ICE will be compared with the conventional marine gas engine (MGE) developed by CATERPILLAR - model G3508, whose specifications are described in [20]. It is proposed to use two engines operating at 75% load to generate a nominal power equal to 750 kW like the net electrical power generated by the proposed hybrid system.

3 Results and discussions

3.1 Thermodynamic analysis results of the baseline configuration

By running the WTEMP model at the baseline configuration (50% SOFC + 50% ICE), the thermodynamic results in terms of mass flow rate, temperature, pressure, enthalpy, entropy, and total exergy are presented in Table 2 for the most critical stream flows in the hybrid system.

Table 2. Thermodynamic properties of the most critical stream flows.

Stream No.	Mass flow (m)	Temperature (T)	Pressure (p)	Enthalpy (h)	Entropy (s)	Total Exergy (E)
	kg/s	°C	bar	kJ/kg	kJ/kg.K	kW
F1	0.0136	27	5.00	-4641	-5.8	701

F2	0.0136	829	4.95	-1770	-1.5	723
F3	0.0260	27	2.40	-3738	-4.1	1051
F4	0.0422	185	0.93	-5119	-1.0	1125
RF	0.0441	686	3.63	-8724	-0.2	765
A1	0.0876	870	1.00	-9659	1.5	270
A5	0.0264	88	0.98	-11150	-0.6	58
A6	0.0879	544	0.98	-10310	0.9	230
A8	0.0161	547	0.93	-7345	2.2	82
O2	0.7178	721	1.00	657	1.4	271
O3	0.6743	870	1.00	827	1.6	341
S3	0.0303	538	4.15	-12400	-1.1	36
S4	0.0303	800	3.82	-11810	-0.5	48

To investigate the thermodynamic performance of the hybrid SOFC-ICE, the exergy flow on all components of the proposed configuration was analyzed while modeling and simulating the baseline scenario as shown in Figure 2.

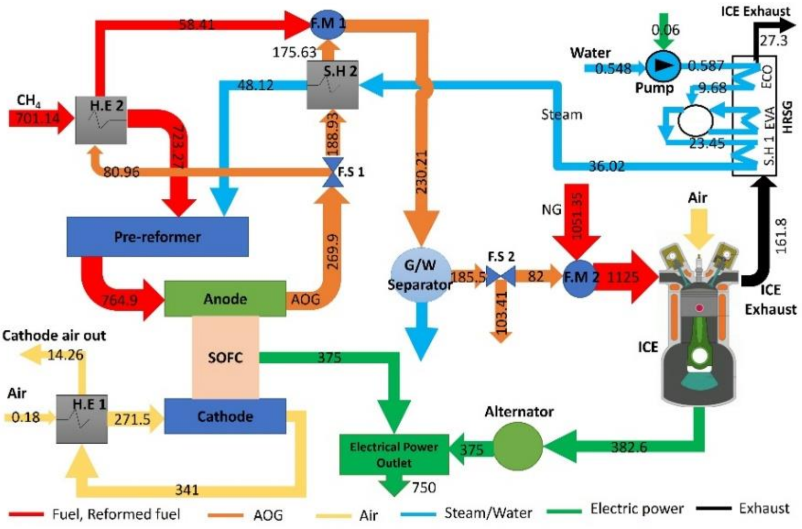

Fig. 2. Exergy flow diagram of the baseline configuration [kW]

As shown in Figure 2, the exergy flow rate of AOG in the A6 stream is 230.21 kW after using AOG to heat steam and CH_4 in S.H2, and H.E2, respectively, while the exergy rate of AOG supplied into ICE is equal to 82 kW, that implies that the proposed configuration can recover 35.62% of AOG exergy to generate additional power and save fuel used in ICE.

Furthermore, the process of exergy destruction is analyzed based on the baseline scenario, and the contribution of each component in the total exergy destruction is presented as a percentage as shown in Figure 3.

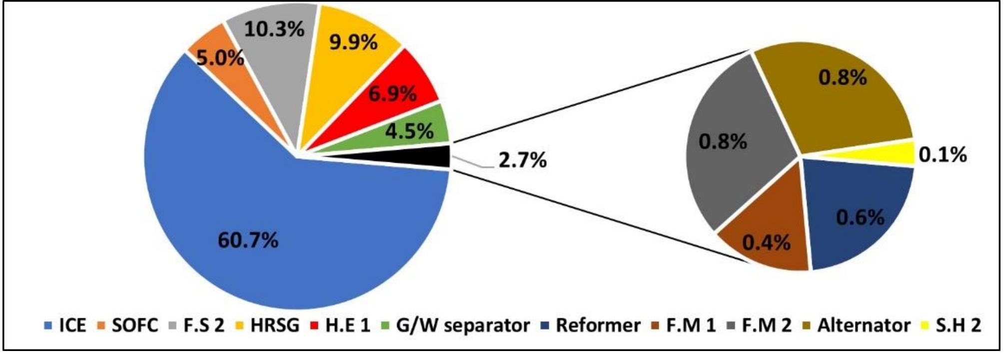

Fig. 3. Contribution percentage of each component in total exergy losses

As shown in Figure 3, the ICE causes the highest exergy losses in the proposed layout (612.64 kW - 60.7%), followed by the flow separator, HRSG, and heat exchanger (103.38 kW (10.3%), 99.03 kW (9.9%), and 69.76 kW (6.9%)), respectively. ICE exergy losses are due to significant irreversibility associated with chemical reactions and heat transfer across the ICE. Moreover, the flow separator contributes to a high exergy destruction rate because of the destroyed exergy exerted in the exhaust of the A9 stream. The evaporator is considered the most contributor to the exergy losses of HRSG due to temperature differences in its thermal reactions. The temperature difference between O3 and O1 streams resulted in high physical exergy destruction of H.E 1 besides the exergy lost in cathode exhaust as presented in Figure 2.

The electric power capacity of SOFC and ICE in the proposed configuration is 375 kW each. The SOFC efficiency is 54.15%, while the efficiency of the integrated ICE excluding and including the energy input from the hydrogen existing in AOG equals 36.05% and 34.16%, respectively. The efficiency of the hybrid system is 44.1%, 12.01% higher than that of the conventional marine gas engine operated by the same composition of natural gas and the same power output of 750 kW. The exergy efficiency of the hybrid system is 42.64% with total exergy destruction equal to 1008.51 kW.

3.2 Effect of power split on hybrid system performance

The optimum integration between SOFC and ICE from efficiency and performance perspectives can be investigated by varying the percentages of load sharing of each power system. In this study, the overall nominal power of the hybrid system is assumed to be fixed at 750 kW, while the tested power splits between SOFC and ICE and their power capacities are presented in Table 3. For ease of comparison process, the fuel utilization, current density, pre-reforming ratio, and AOG-NG blend volumetric percentages are fixed at 80%, 5000 A/m^2, 10%, and 30-70%, respectively.

Table 3. Power capacities and load sharing between SOFC and ICE in the proposed hybrid system

Case number	Load sharing (SOFC – ICE)	Power capacity (kW)
1	33% - 67%	247.5 – 502.5
2	50 % - 50 %	375 – 375
3	67 % - 33 %	502.5 – 247.5

The thermodynamic analysis is repeated for cases 1 and 3 to determine the effect of SOFC/ICE load sharing on the operating parameters of the layout and the different components as shown in Table 4. Because of fixing the fuel utilization in the three analyzed cases, the composition of H_2, CO_2, and CO existing in AOG blending with NG in ICE are constant at 11.54%, 15.23 %, and 3.23%, respectively.

Table 4. Results of the simulations at different power splits

Stream	Case 1			Case 2			Case 3		
No.	**m [kg/s]**	**T[°C]**	**E [kW]**	**m [kg/s]**	**T[°C]**	**E [kW]**	**m [kg/s]**	**T[°C]**	**E[kW]**
F2	0.0089	834	477	0.0136	829	723	0.0182	836	969
F3	0.0349	27	1410	0.0260	27	1051	0.0172	27	694
F4	0.0566	186	1509	0.0422	185	1125	0.0279	186	743
A1	0.0578	874	178	0.0876	870	270	0.1172	876	362
A8	0.0217	550	111	0.0161	547	82	0.0107	551	55
O2	0.4625	724	176	0.7178	721	271	0.9379	726	358
O3	0.4339	874	221	0.6743	870	341	0.8798	876	450
S4	0.0201	800	32	0.0303	800	48	0.0408	800	65

Based on the results, the SOFC efficiency is constant at 54.2% over the three simulated cases due to the assumption of fixing the current density and SOFC fuel utilization, while the ICE efficiency is constant at 36% because of using the same blending fraction between AOG and NG in the three cases which leads to a constant lower heating value of the utilized fuel in the ICE. On the other hand, the hybrid system efficiency is enhanced with the increase of SOFC load sharing from 33% to 67% when compared with the efficiency of a conventional MGE that has the same rated power of 750 kW as shown in Figure 4. The improvements are 9.2%, 12%, and 15.3 % for cases 1,2, and 3, respectively.

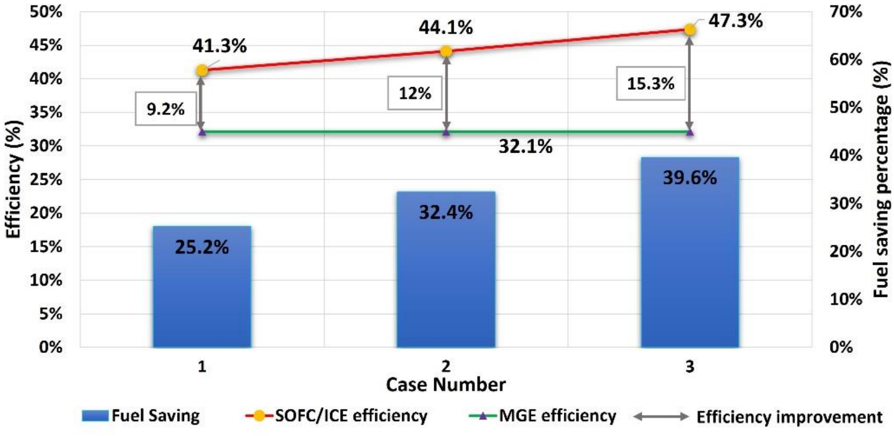

Fig.4. The effect of different power splits in the integration between SOFC and ICE at a constant power output of 750 kW.

The maximum efficiency of the hybrid system (47.3%) occurred in the third case as the highest efficiency component (SOFC) is privileged in terms of power capacity. Nevertheless, even once integrating a small load share of SOFC in the hybrid system as simulated in case 1, this brings to a significant efficiency improvement and fuel saving when compared to conventional MGE powered by NG only as shown in Figure 4.

The environmental potential benefits of the integration between SOFC and ICE can be investigated by calculating the CO_2 emissions from both power plants. The volumetric and weight fractions of CO_2 emissions in the exhaust gas from the SOFC (stream O4) at different power splits are 0.035% and 0.053%, respectively, while these fractions from ICE's exhaust gas (stream E2) are 9.6% and 15.03%, respectively. Furthermore, the volumetric and weight fractions of CO_2 emissions in AOG (stream A9) are 50.7 % and 85.5 %, respectively. Like fuel saving, the increase in load share of SOFC in the proposed integration leads to more improvement from the environmental point of view as the saving in CO_2 emissions are increased from 22.4 % to 37.5 % when increasing the load share of SOFC from 33% to 67%.

4 Conclusions

The current paper studies hybridizing SOFC with ICE as a potential power system for ships, the suggested system includes an external reformer and a heat recovery steam generator, the SOFC is fed by pure methane while SOFC anode off-gas is blended with natural gas to power the ICE. The thermodynamic analysis has been conducted by using an in-house software called WTEMP developed by TPG at the University of Genoa. Three load-sharing strategies were studied to study their effect on hybrid system efficiency, fuel saving, and CO_2 emissions. The main results are as follows:

a) The highest contribution in the exergy destruction of the baseline configuration (50% SOFC + 50% ICE) is associated with ICE by 60.7% of the overall exergy destruction because of the significant irreversibility associated with chemical reactions and heat transfer.
b) Over the three simulated cases, the SOFC efficiency and the integrated ICE equals 54.2%, and 36%, respectively. While the hybrid system efficiency is enhanced by increasing the sharing load of SOFC as it reaches 47.3% when sharing 67% from SOFC with an improvement of 15.3 % over conventional MGE.
c) Furthermore, the integration of SOFC and ICE achieves fuel savings when compared with MGE of about 25.2% and 39.6% when sharing 33% and 67% of load by SOFC, respectively. While CO_2 emissions are reduced by about 37.5% in the case of using 67% of the load share by SOFC.

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