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STEAM AND SOFC BASED REFORMING OPTIONS OF PEM FUEL CELLS FOR MARINE APPLICATIONS

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Summary

The need for green energy sources without or with low emissions in addition to improve the using efficiency of current fossil fuels in the marine field makes it important to replace or improve current fossil-fuelled engines. The replacement process should work on narrowing the gap between the most scientific innovative clean energy technologies and the concepts of feasibility and cost-effective solutions. Early expectations of very low emissions and relatively high efficiencies have been met in marine power plants using fuel cell. In this study, steam and SOFC based reforming options of natural gas for PEM fuel cells are proposed as an attractive option to limit the environmental impact of the marine sector. The benefits of these two different reforming options can be assessed using computer predictions incorporating chemical flow sheeting software. It is found that a high overall efficiency approaching 60% may be achieved using SOFC based reforming systems which are significantly better than a reformed PEM system or an SOFC only system.

Key words: Solid oxide fuel cell; Polymer electrolyte membrane fuel cell; reforming options, marine applications.

1. Introduction

Use of the conventional marine fuels as a source of energy for traditional marine power plant have been faced a lot of barriers due to its demerits especially regarding to the environmental and economic point of views. Environmentally, it was shown by [1] that in 2000, 15% of all global NO_x emissions and 4-9% of global SO_2 emissions have been emitted around by ocean-going ships. In addition, IMO revealed in 2009 that ships had emitted about 25 million tons of NO_x during the year 2007. To eliminate the harmful NO_x emissions; the IMO regulations had planned to achieve NO_x emissions reduction through three Tiers which could require reduction in nitrogen oxides by 85% onboard ships [2]. Regarding eliminating of dangerous SO_x emissions, IMO planed using of marine fuel containing 0.1% sulfur onboard ships beginning by January 2015[3, 4, and 5]. In addition economically, the prices of the conventional marine fuels showed a great fluctuation through the past few years and still present the main part of ship operating budget. To rise above, the shipping industry started search for alternative fuels that are also price competitive comparing to typical marine fuels like marine diesel oil (MDO). After over 20 years of preparatory steps, Liquefied Natural Gas (LNG) can be used as an alternative fuel in the shipping industry [6]. LNG-propelled ships will be particularly attractive in case the vessel will enter Emission Control Areas (ECAs) since they can meet Tier III emission levels and the SO_x requirements without any treatment of the exhaust gas. It is estimated that almost 70% of the world fleet will be entering ECAs in the near future [7, 8].

Some guidelines were set for installing of fuel-cell systems (FC systems) permanently on ships and boats in different classification societies rules [9]. It described the technical requirements for the safe operation of FC systems. One of these guidelines belong to Det Norske Veritas (DNV) and Germanischer Lloyd (G.L) classification society, which revealed some consideration that should be taken into account regarding safety functions, installation, fuel transfer system, fuel storage, fuel conditioning, and fuel distribution [10, 11]. Lloyd's Register in its guidelines [9] showed the importance of study safety of the ship, safety of personnel, and safety of machinery in case of use fuel cell onboard ships to be comply with standards of Safety of Live at Sea (SOLAS) convention. There are five main types of fuel cells being developed in the stationary fuel cell market. These cells are referred to the type of electrolyte used within the system. Two of those are considered candidates for shipboard use, the Solid Oxide Fuel Cell (SOFC) and the Proton Exchange Membrane fuel cell (PEM) as they are available in the market size, most of materials used in their manufacturing are available, and the development of their efficiency is high [12, 13].

Steam Reforming (SREF), Partial Oxidation (POX), Auto-thermal Reforming (ATR), SOFC are the four major hydrocarbon-reforming technologies for PEM fuel cells. Steam reforming and auto thermal reforming appear to be the most competitive fuel processing options in terms of fuel processing efficiencies. Partial Oxidation (POX) method has a less fuel processing efficiency than steam reforming method [14, 15]. The primary purpose of this paper is to identify favorable operating conditions at which natural gas fuel is converted to hydrogen rich gas mixtures via SREF and SOFC internal reforming processes at reasonable fuel reforming efficiencies to be used in PEMFCs. Natural gas is selected for hydrogen rich gas production for PEMFC due to its favorable composition from lower molecular weight compounds compared with other fossil fuels. In addition, a simulation study of the different components of the selected two reforming options for PEM fuel cell will be conducted. Also, some of the performance parameters of the total system operated with natural gas fuel will be discussed as a proposed marine power plant for ships.

2. Simulation steps for PEM fuel cell

PEM fuel cells require a high purity hydrogen source for operation. Hence, the projected commercialization of PEMFC powered ships requires a readily available hydrogen source, which is either used directly or is produced in an on-board fuel processor. Hydrogen can be produced by reforming a hydrocarbon fuel into a hydrogen rich gas gases. The reformed fuel often contains other gases such as carbon monoxide (CO) that are detrimental to PEMFC operation. The CO contained in the reformat must be further reduced to capacity 10 ppm prior to feeding to the PEM fuel cell [16, 17, and 18]. The investigated PEM fuel cell system consists of three sections and their components as shown in Fig. 1. The first section is fuel processing and clean-up section. It includes steam reforming or SOFC with internal reforming (two cases investigated), high and low temperature shift reactors (HTS and LTS), and preferential oxidation reactor (PROX). The second section is PEM fuel cell which contains fuel cell stack and DC/AC converter. The third section is the auxiliary units like pumps, compressor, expander, heat exchangers, heaters, coolers, and burner. For all sections, all reactors are simulated to operate under equilibrium conditions.

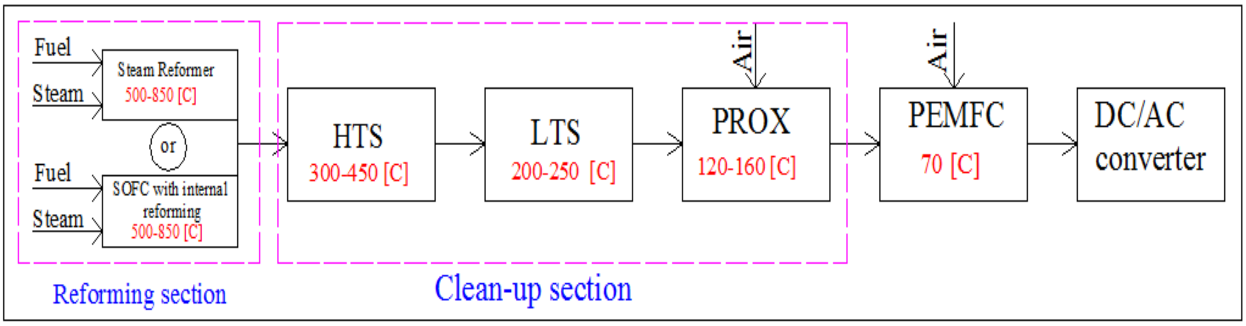

Fig. 1 Typical inlet and outlet steam temperature ranges for PEMFC reactors

SOFC based reforming option for PEM fuel cell is a combined cycle in which both SOFC and PEM fuel cell are combined. The system can be shown in Fig. 2 and it works as follows: the internal reforming SOFC is run under conditions that give low fuel utilization. This enables a high power output for a relatively low stack size. Unused fuel from SOFC appears in the anode exhaust where it undergoes shift reaction, followed by a process stage when the final traces of carbon monoxide are removed. At this stage, the gas comprises mainly hydrogen and carbon dioxide, with some steam. This gas, once it is cooled, is suitable for use as a fuel in the PEM stack [19, 20, 21, and 22].

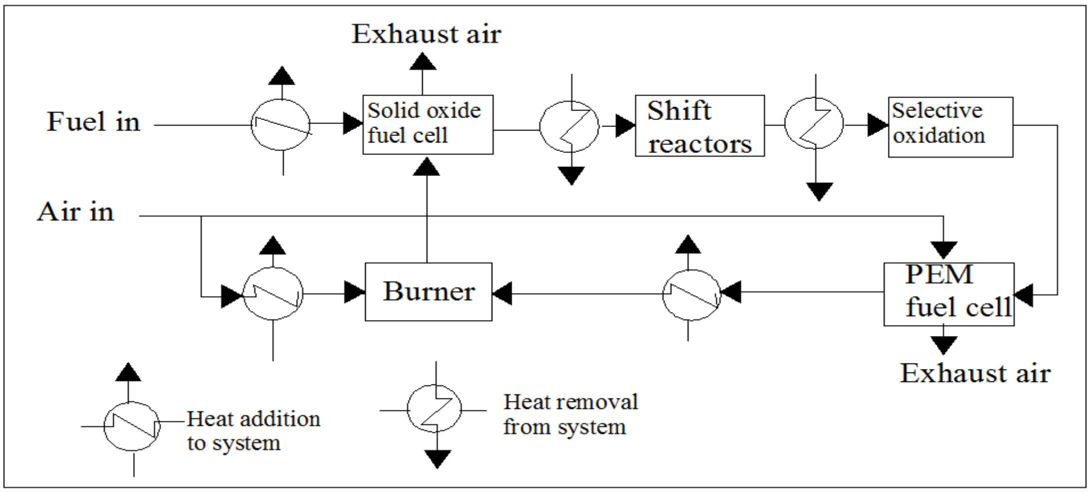

Fig. 2 Reforming option based on solid oxide fuel cell used for PEM fuel cell

The main difference in SOFC stack cost compared to PEMFC cost relates to the simpler system configuration of the SOFC system. This is mainly due to the fact that SOFC stacks do not contain the high-cost precious metals that PEFCs contain. In addition, the cost of SOFC balance of plant is low by comparison to the PEMFC [19]. However, the cost of the recuperating heat exchangers partially offsets that. This is offset in part by the relatively complex manufacturing process required for the SOFC electrolyte plates and by the lower power density in SOFC systems [23, 24].

2.1 Brief description of fuel cell processing and clean up sections

The fuel processing efficiency covers the section from the hydrocarbon feed section to the fuel cell including all reforming and clean-up reactors and auxiliary equipment.

The pressure is kept constant at 3 bars in this study. The operating parameters of reactors are changed parametrically to determine the best operating conditions. The limitations set by the catalysts and hydrocarbons involved are also considered. The simulation code is capable to calculate the steady state product compositions taking into account the incoming stream compositions under the defined operation conditions.

The aim is to convert as much hydrogen in the fuel into hydrogen gas at acceptable yields in an efficient manner while decreasing CO and CH_4 formation. Lower SC ratios favor soot and coke formation, which is not desired in catalytic steam and auto thermal reforming processes.

2.2 Chemical reaction scheme

The fuel processor is simplified to a steam reformer or SOFC reactor, two water gas shift reactors and a preferential oxidation reactor for the modeling purpose. Steam reforming is a method of hydrogen production used on a large scale industrially, most notably in the production of ammonia. Steam reforming involves both the reforming reaction Eqs. (1) and (2) and the water-gas shift reaction Eq. (3). These are carried out at elevated temperatures over a supported nickel catalyst.

$$CH_4 + H_2O \rightarrow CO + 3H_2 \quad (1)$$

$$CH_4 + 2H_2O \rightarrow CO_2 + 4H_2 \quad (2)$$

$$CO + H_2O \leftrightarrow CO_2 + H_2 \quad (3)$$

In case of SOFC internal reforming (SOFC-IR), the electrolyte, which divides the stack into two electrodes, acts as an electronic barrier and avoids the direct chemical reaction of the fuel at the anode with the oxygen at the cathode. At the cathode, molecular oxygen combines with electrons and is reduced to negatively charged ions (O^{2-}) with the aid of a catalyst [19, 23].

The degree to which an anode supports direct oxidation will then impact the degree of the reforming of the fuel that is required, which in turn typically impacts the balance of plant complexity and cost [23, 25]. The net cell reaction is thus written as:

$$\mathrm{CH_{4,anode}} + 2\mathrm{O_{2,cathode}} \Leftrightarrow 2\mathrm{H_2O_{,anode}} + \mathrm{CO_{2,anode}} \quad (4)$$

In order to reduce the CO concentration out of the LTS, the preferential oxidation reaction (PROX) is performed.

$$CO + 1/2\ O_2 \rightarrow CO_2 \quad (5)$$

$$H_2 + 1/2\ O_2 \rightarrow H_2O \quad (6)$$

2.3 Simulation of the steam reformer and SOFC internal reforming

Steam reforming is a method for hydrogen production from hydrocarbon fuels such as natural gas. This is achieved in a processing device called a reformer which reacts steam at high temperature with the natural gas fuel. In this study, both steam reforming and SOFC internal reforming reactors are modelled using HYSYS conversion reactors.

2.4 Simulation of water gas shift reactor

The CO content can be reduced to about 0.5% by reacting it with water at lower temperatures to produce additional hydrogen according to the WGS reaction (Eq. (3)). Commercial hydrogen plants generally perform the WGS in two stages: (i) High-temperature shift at 300-450°C using an oxide catalyst, and (ii) low-temperature shift at 200 – 250 °C using copper zinc oxide. Heat exchangers are required between shift reactors to provide cooling, and the conversion in an adiabatic reactor is limited because the reaction is exothermic and the temperature increases as the reaction proceeds. In this study, WGS reactors are modeled using equilibrium reactor. By using equilibrium reactor, HYSYS will determine the composition of the outlet stream given the stoichiometry of all reactions occurring and the value of equilibrium constant for each reaction.

2.5 Simulation of preferential oxidation reactor

Carbon monoxide is a poison to the precious metal catalyst in the anode of the PEM fuel cell. Preferential oxidation (PROX) is a reactive approach to destroy CO in the reformat composition. PROX of CO is typically used to reduce CO to the part per million levels required for the PEM fuel cell. The catalyst and conditions must be selected to minimize the oxidation of hydrogen. For the overall process model heat and material balance, 50% selectivity to CO oxidation is assumed, with the remainder of the oxygen reacting with hydrogen to form water. The PROX reactor was modeled in HYSYS as a conversion reactor based on two reactions to oxidize CO as shown in Eqs. (5) and (6).

3. The present simulation

Figs. 3 and 4 show the two reforming cases of PEM fuel cell system scheme simulation studied by Aspen- HYSYS 3.2 taking into account selected balance plant of plant equipment. The hydrocarbon fuel is first pressurized (2), and then vaporized (5). The vaporized hydrocarbon fuel is divided into two streams: One stream (6) is directed to the burner where it is combusted to provide the necessary process heat, the other stream (7) is mixed in the air-fuel mixer (AFM) with the hot compressed air (12) from the compressor. The air fuel mixture (13) is heated with the hot combustion gases (40) from the combustor up to the required PRE-SR temperature (35).

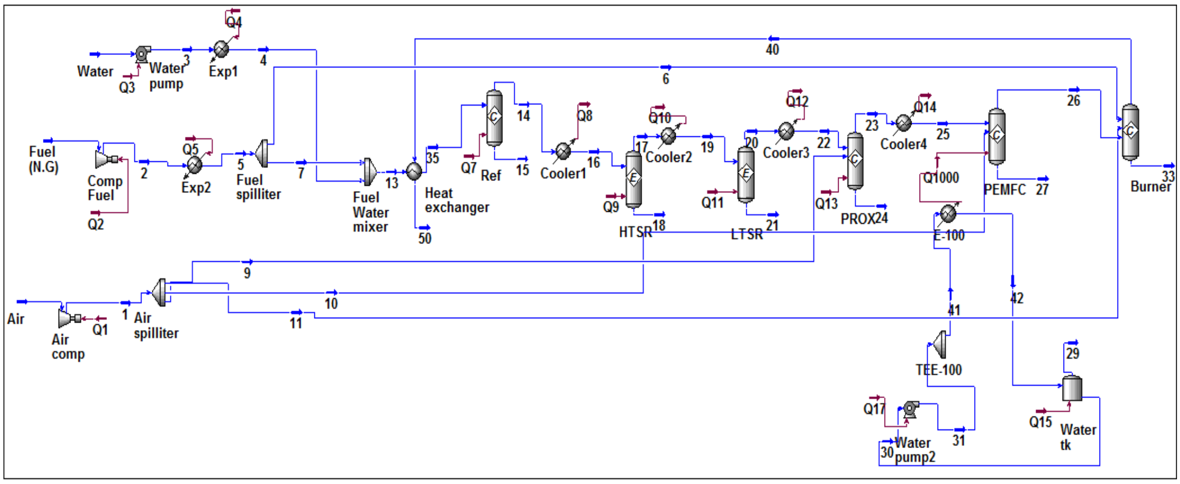

Fig. 3 Actual steam reforming based PEM fuel cell system flow diagram simulated by Aspen HYSYS 3.2.

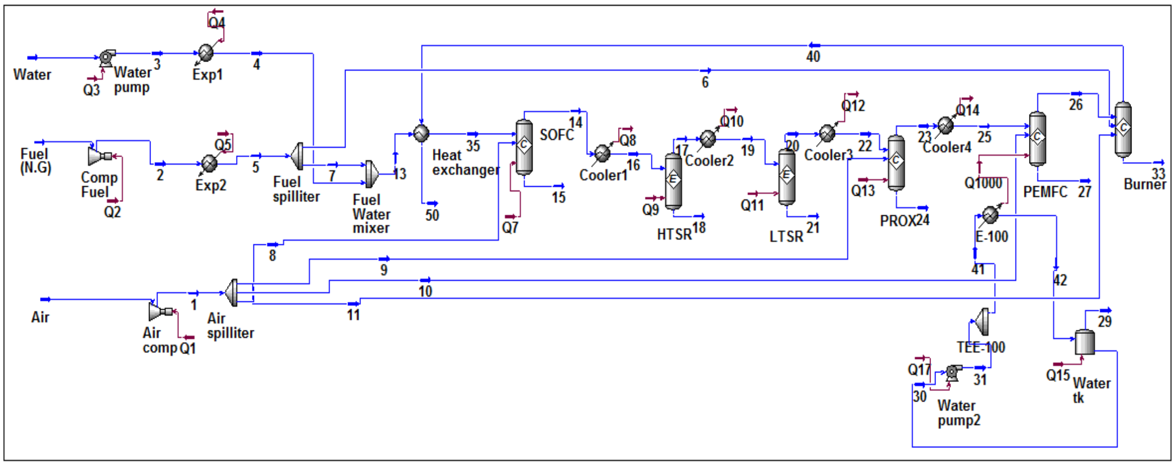

Fig. 4 Actual SOFC based reforming PEM fuel cell system flow diagram simulated by Aspen HYSYS 3.2.

All of the chemical reactions are assumed to occur adiabatically under equilibrium conditions. The gases leaving SOFC reactor (14) are cooled (16) prior to entering the HTS reactor. The gases are further processed in LTS and PROX. The exit gases from the PROX (23) are fed to PEM fuel cell after cooling (25).

It is desired to maximize hydrogen concentration and to minimize carbon monoxide (CO) content considering the requirements of PEM fuel cells. The high and low temperature water- gas shift reactors (HTS and LTS) and the preferential oxidation (PROX) are used to decrease the CO concentration level of the SREF or SOFC reactors exit gas to the desired values.

Compressed air is divided into 4 streams in case of SOFC based reforming PEM fuel cell system: one stream is directed to the SOFC (8) as SOFC reactant; another stream is used in PROX (9); the third stream (10) supplies the cathode air of PEM fuel cell; the fourth air stream is the combustion air (11). Pressurized water (3) is converted to steam (4) to be used in SOFC. Water is circulated (41-42) to cool down the PEM fuel cell.

Anode and cathode off-gases (26) of the PEM fuel cell are combusted together with the hydrocarbon fuel (6). The combustor off- gases are expanded after exchanging heat with the hydrocarbon fuels to heat them up prior to SREF-SOFC entrance to produce additional power. The final burner exit gases (40) are above 500°C. The fuel cell stack is assumed to run under constant temperature and pressure, namely 70°C and 3bars. The PEM fuel cell characteristics are presented in Table 1.

Table 1 The PEM fuel cell characteristics (e-: Electron)

$2H_2 \rightarrow 4H^+ + 4e^-$	Anode Reaction
$O_2 + 4H^+ + 4e^- \rightarrow 2H_2O$	Cathode Reaction
65	Fuel utilization (%)
70	Fuel cell outlet temperature (°C)
3	Pressure (bar)
800	Average cell voltage (mV)
Water	Stack cooling media

Table 2 summarizes the assumed data of different auxiliary system components utilized in the simulation studies. They are based on commercially available units [17, 26].

Table 2 Auxiliary system component data

Component	Parameter	Value
Fuel pump	Adiabatic efficiency (%)	75
Water pump	Adiabatic efficiency (%)	75
Cooling water pump	Adiabatic efficiency (%)	75
Compressor	Adiabatic efficiency (%)	70
Expander	Adiabatic efficiency (%)	75
DC/AC Converter	Conversion efficiency (%)	98

The thermal efficiencies of the REF, HTS, LTS and PROX reactors are η_{REF}, η_{HTS}, η_{LTS} and η_{PROX}, respectively. They are defined as the ratio of the heating values and mass flows of the exit and inlet streams, Eqs. (7) to (11). The heating value of a stream is calculated by the multiplication of its lower heating value (LHV) with its mass flow rate in kg per hour. η_1 presents the fraction of the REF inlet stream heating value to the heating value of the total fuel feed to the system. The remainder is fed to the burner. The total fuel processing efficiency is the product of η_1, η_{REF}, η_{HTS}, η_{LTS} and η_{PROX} as shown in Eq. (12).

$$\eta_1 = \frac{\dot{m}_7 \times \mathrm{LHV}_7}{\dot{\mathrm{m}}_\mathrm{F} \times \mathrm{LHV}_\mathrm{F}} \tag{7}$$

$$\eta_{\mathrm{REF}} = \frac{\dot{m}_{16} \times \mathrm{LHV}_{16}}{\dot{\mathrm{m}}_{35} \times \mathrm{LHV}_{35}} \tag{8}$$

$$\eta_{\mathrm{HTS}} = \frac{\dot{m}_{19} \times \mathrm{LHV}_{19}}{\dot{\mathrm{m}}_{16} \times \mathrm{LHV}_{16}} \tag{9}$$

$$\eta_{\mathrm{LTS}} = \frac{\dot{m}_{22} \times \mathrm{LHV}_{22}}{\dot{\mathrm{m}}_{19} \times \mathrm{LHV}_{19}} \tag{10}$$

$$\eta_{\mathrm{PROX}} = \frac{\dot{m}_{25} \times \mathrm{LHV}_{25}}{\dot{\mathrm{m}}_{22} \times \mathrm{LHV}_{22}} \tag{11}$$

$$\eta_{\mathrm{FP}} = \eta_1 \times \eta_{\mathrm{REF}} \times \eta_{\mathrm{HTS}} \times \eta_{\mathrm{LTS}} \times \eta_{\mathrm{PROX}} \tag{12}$$

The PEM fuel cell module has been simulated using the PEM fuel cell characteristics presented in Table 2. The SOFC and PEM fuel cell stack efficiencies depend on fuel utilization coefficient (U_f), stack voltage, and DC/AC conversion efficiencies. Fuel cell voltage (V_{cell}) is the difference between cell voltage at no load, which can be called open circuit voltage and the specific fuel cell irreversibility or voltage drop. The following Eq. (13) shows the operating voltage of a fuel cell at a current density (i_{den}) [19, 27].

$$\mathrm{V_{cell}} = \mathrm{E_o} - (\mathrm{i_{den}} \times \mathrm{r}) - \mathrm{A} \times \ln(\mathrm{i_{den}}) + \mathrm{m} \times \mathrm{e}^{(\mathrm{n} \times \mathrm{i_{den}})} \tag{13}$$

$$\eta_{\text{stack voltage}} = \frac{\mathrm{V_{cell}} \times \mathrm{U_f}}{\mathrm{E_o}} \tag{14}$$

$$\eta_{\mathrm{DC/AC}} = 0.98 \tag{15}$$

$$\eta_{\mathrm{FC}} = \eta_{\text{stack voltage}} \times \eta_{\mathrm{DC/AC}} \tag{16}$$

In Eq. (13), E_o is the open circuit voltage, ' i_n' internal current density, 'A' is slope of Tafel curve, 'm' and 'n' are constants, 'r' is specific resistance. Typical values of these constants for a SOFC and PEM fuel cell systems are given in Table 3.

Table 3 Typical values of over voltage parameters [19, 28, 29, 30, and 31].

Constant	SOFC	PEMFC
E_o (V)	1.01	1.031
r (kΩcm^2)	2.0×10^{-3}	2.45×10^{-4}
A (V)	0.002	0.003
m (V)	1.0×10^{-4}	2.11×10^{-5}
n (cm^{2}mA^{-1})	8×10^{-3}	8×10^{-3}

Auxiliary units comprise pumps, compressor, expander, heat exchangers, heaters coolers and burner. The auxiliary system efficiency (η_{Aux}) is calculated as follows:

$$\eta_{motor} = 0.9 \tag{17}$$

$$P_{par} = \frac{P_{P1} + P_{P2} + P_C}{\eta_{motor}} \tag{18}$$

$$\eta_{Aux} = 1 + \frac{(P_E - P_{par})}{P_{PEM,AC}} \tag{19}$$

Extensive heat integration is sought within the study to achieve acceptable overall system efficiency levels. The overall system efficiency ($\eta_{net.el}$) is calculated as the product of fuel processing (η_{FP}), both SOFC and PEM fuel cell (η_{FC}) and auxiliary (η_{Aux}) system efficiencies.

$$\eta_{net.el} = \eta_{FP} \times (\eta_{PEMFC} + \eta_{SOFC}) \times \eta_{Aux} \tag{20}$$

4. Results and discussion

The performance of both SOFC and PEM fuel cells can be described by the polarization curve, which relates the cell voltage to its current density. This polarization curve is affected by the losses of the fuel cell. Fig. 5 shows the polarization curves of both SOFC and PEM fuel cells. As the cell current density increases, there will be a drop of the output voltage of the fuel cell. This drop of the cell voltage will be higher in SOFC than that of PEMFC. As the current density reaches its maximum value, the SOFC voltage drops sharply to zero before than PEMFC voltages does.

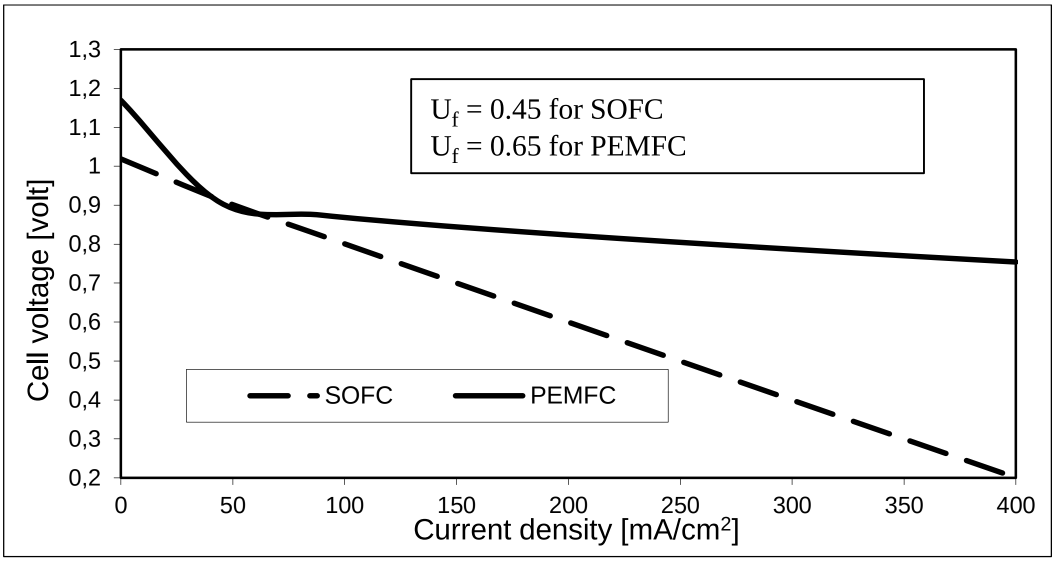

Fig. 5 SOFC and PEMFC polarization curves

In the following, the results obtained for the reforming of natural gas using SREF and SOFC-PEM shown in Fig.s 3 and 4 are presented. The components results for the selected reforming options for PEM fuel cell. The operating points for the SOFC and PEM fuel cells are at cell output current density of 250 mA/cm^2, cell voltage and fuel utilization coefficient of (0.804 volts, 65%) and (0.499 volts, 45%) for PEM and SOFC respectively. Moreover, AF and SC ratios are (5, 8.25) and (7.75, 8.5) for SREF and SOFC reforming options respectively. In addition, the percent of the fuel supplied to the burner is 1.4% from the supplied fuel to the system. Tables 4 and 5 show the results of selected system points calculated under the prescribed operating conditions applied in the two cases of reforming.

Table 4 Simulation results for selected system points calculated under the prescribed operating conditions applied in SREF-PEM

Stream	Fuel	Air	Water	5	6	13	8	10	11
Temperature (°C)	25	20	25	200	200	495	206	206	206
Pressure (kPa)	120	100	170	300	300	300	400	400	400
Mass flow(kg/hr)	40	200	330	40	0.55	369	1.5	55	143
Stream	35	14	17	19	20	22	23	25	40
Temperature(°C)	500	850	350	200	250	120	150	70	513
Pressure (kPa)	300	300	168	170	170	163	163	300	300
Mass flow (kg/hr)	369	369	369	25	25	25	25	25	570

Table 5 Simulation results for selected system points calculated under the prescribed operating conditions applied in SOFC-PEM

Stream	Fuel	Air	Water	5	6	13	8	10	11
Temperature (°C)	25	20	25	200	200	455	162	162	162
Pressure (kPa)	120	100	170	300	300	300	300	300	300
Mass flow(kg/hr)	40	310	340	40	0.55	379	105	65	173
Stream	35	14	17	19	20	22	23	25	40
Temperature(°C)	500	850	350	100	250	120	150	70	536
Pressure (kPa)	300	300	168	170	170	163	163	300	300
Mass flow (kg/hr)	379	450	450	450	450	450	451	451	960

The product compositions and LHVs results for SREF and SOFC cases at the operating points can be shown in the following Figs. 6 and 7. With the developed system models which are implemented in the HYSYS 3.2 process simulator, effluents from all reactors are simulated. A considerably wide SC and AF ratios has been changed to see its effect on hydrogen yield and CO formation. The selected operating point achieves high reformer efficiency and acceptable CO content for PEM. CO content in the product steams changes from 2.3% and 3.3% to 0.0 for steam and SOFC based reforming options before entering PEMFC.

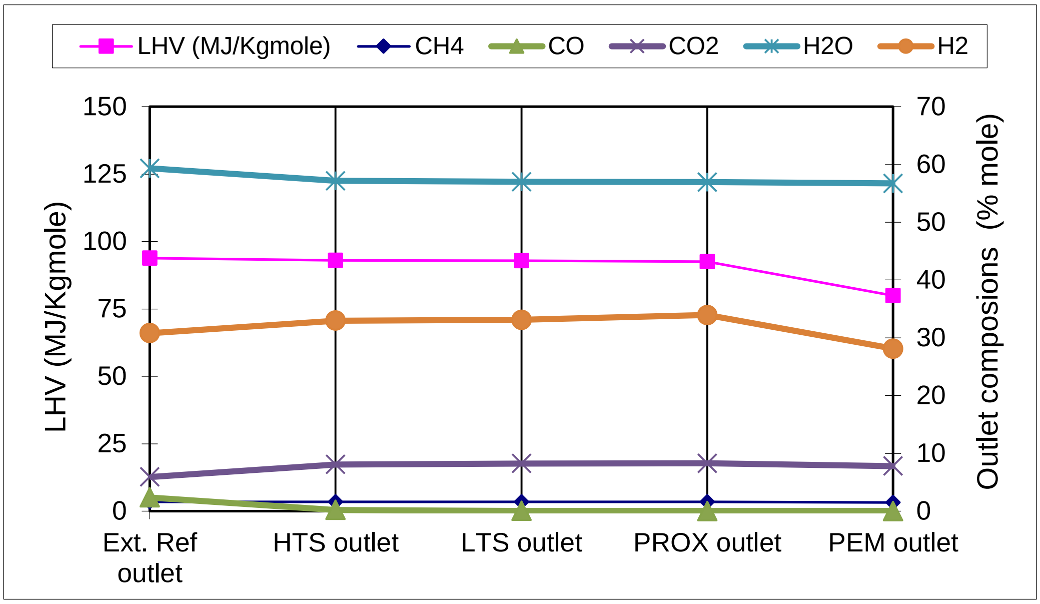

Fig. 6 Product compositions and LHV values of steam reforming based fuel preparation reactors.

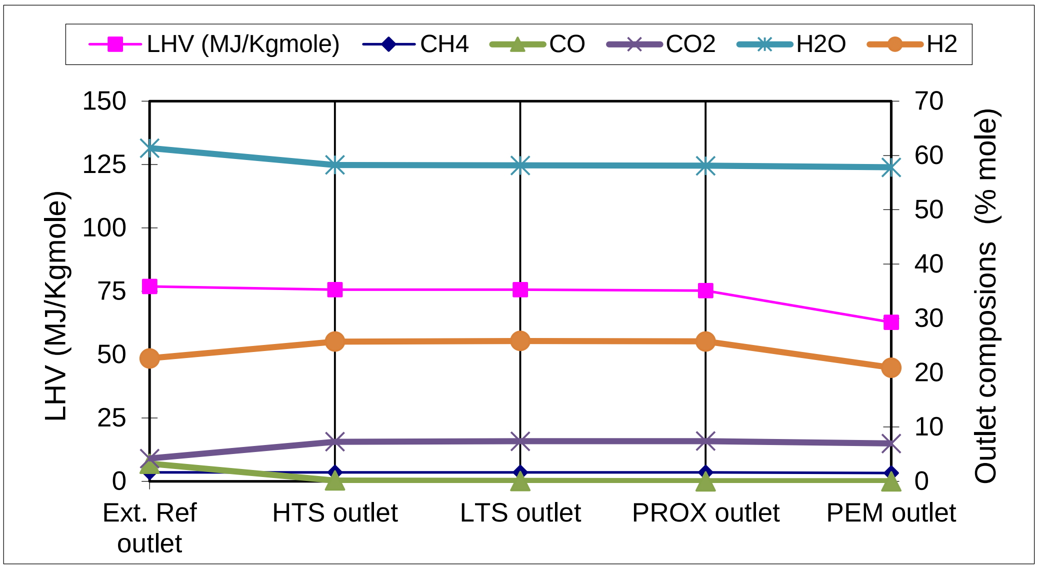

Fig. 7 Product compositions and LHV values of SOFC based fuel preparation reactors.

Fig. 8 shows the molar fractions and product lower heating values of all components in the effluent of the two reformer reactors of the natural gas fuel processor system. In SREF case, 100% methane is converted to produce 30.8% hydrogen, 6.0% CO_2 and 2.4% CO. In addition, under these conditions, oxygen is 100% consumed. Simultaneously, in the case of SOFC-PEM, 100% methane is converted to produce 22.6% hydrogen, 4.2% CO_2 and 3.2% CO.

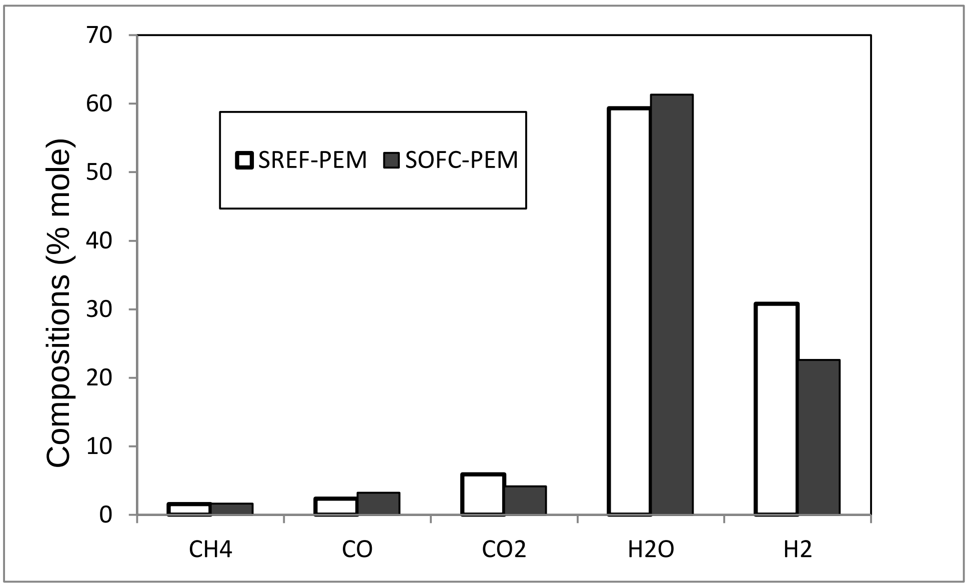

Fig. 8 The molar compositions of the two cases of reformer products

The operating parameters of the reforming process are of utmost importance to achieve the desired high hydrogen and low CO content product gases along with acceptable fuel conversion efficiency level. The total air to fuel ratio range studied is between 3.0 and 5.0 for the SREF-PEM as shown in Fig. 9. Similar approach has been adopted for SOFC-PEM; in this case air to fuel consumption (m_8/m_f) has been changed between 1.0 and 3.0 as shown in Fig. 10. It can be noticed that, in the case of SREF-PEM, the reformer efficiency as well as the hydrogen content of the product gases steadily decreases as the air to fuel ratio decreases. In addition, increasing the steam flow rate increases the reformer efficiency but this increase will affect the following reformers like PROX and burner exhaust temperature. In the other case, the reformer efficiency decreases as the reformer air to fuel ratio decreases at low steam to carbon ratios. In contrast, at high steam to carbon ratios the reformer efficiency increases as the air to fuel ratio decreases.

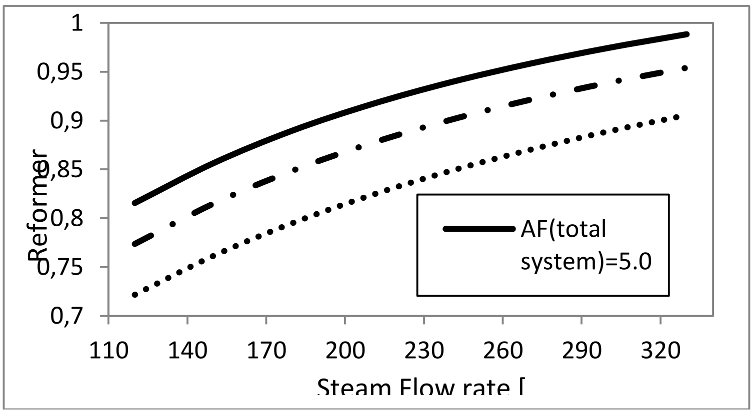

Fig. 9 Reformer efficiency as a function of steam flow rate and total system AF ratio (SREF-PEM)

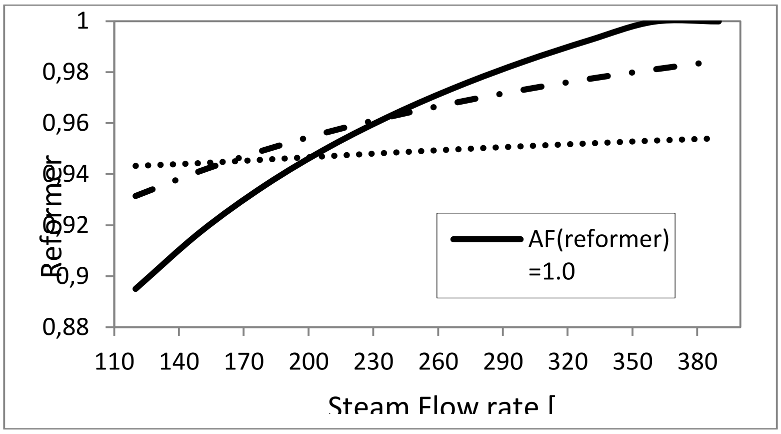

Fig. 10 Reformer efficiency as a function of steam flow rate and reformer AF ratio (SOFC-PEM)

The two reforming options based fuel-processing, fuel cell, auxiliary and overall system efficiencies of the investigated natural gas fuel are presented in Table 6. The values indicate that reforming of natural gas either by steam reforming or by SOFC based reforming option achieves high fuel processing efficiency. Moreover, natural gas based systems do not require the pre-reformer unit compared with liquid fuel systems due to their high lower molecular weight hydrocarbon, namely CH_4 content [32, 33]. In addition, both fuel cell efficiency and net electrical efficiency depends on fuel utilization coefficient fuel cell output current density.

Table 6 SREF and SOFC based fuel processing options for PEM fuel cell system

System	U_f	η_{FP}	η_{FC}		η_{Aux}	$\eta_{net.el}$
			PEMFC	SOFC		
Reformer-PEM	0.65	96.48	50.71	------	90.7	44.37
SOFC-PEM	0.45 (SOFC)-0.65(PEMFC)	95.27	50.71	22.26	90.0	62.56

It can be noticed from Table 6 that, heat integration within reforming, cleanup sections and PEM fuel cell components are the most important factor to achieve high PEMFC efficiency levels. These efficiency levels will be necessary to achieve the aims of the international emission regulations and to improve the total efficiency of marine power plants.

The obtained net electrical efficiency levels are at 44% and 62% for SREF and SOFC based reforming options for PEM fuel cells. These efficiency levels are higher than those of Otto engines. Therefore, both Steam reforming and SOFC internal reforming options of natural gas offers an efficient, and can be widely used for hydrogen production, and for near and mid-term energy provide with a good environmental benefits. Natural gas is a convenient, easy to handle, hydrogen feedstock with a high hydrogen to-carbon ratio. The cost of hydrogen produced by methane is acutely dependent on natural gas prices.

5. Conclusions

- PEM fuel cells generate electrical power from air and from hydrogen or hydrogen rich gas mixtures. Therefore, there is an increasing interest in converting current hydrocarbon based transportation fuels such as Natural gas into hydrogen rich gases acceptable by PEM fuel cells on board ships. In addition PEM fuel cell fuelled by natural gas is an attractive option to limit the environmental impact of the marine sector in order to satisfy the requirements of international regulations and to achieve high efficiency.

- As a model for application, a SREF and SOFC based reforming options for PEM fuel cell system at cell output current density of 250 mA/cm^2, and fuel utilization coefficients of 65% and 45% for PEM and SOFC respectively has been carried out. Among the conditions studied, the highest fuel processing efficiency is achieved at about 96% with AF= 5.0 and SC=8.25 using SREF-PEM fuel cell system. Also, SOFC-PEM fuel cell system resulted in high fuel processing efficiency at 95% incorporating AF and SC ratios of 7.75 and 8.5 respectively.
- The simulation results of SREF-PEM showed that, the obtained net electrical efficiency level is at 44% which is higher than those of Otto engines and competitive to that of diesel engines. In SOFC-PEM fuel cell, the advantages of each type of fuel cell are enhanced by operating in synergy. It is found that a high overall efficiency approaching 60% can be achieved using SOFC–PEM systems which are significantly better than a SREF-PEM system or an SOFC only system.
- Finally, high PEM fuel cell system efficiency levels can be achieved only with intensive heat integration within the PEMFC systems. Hence, heat integration within PEMFC components system studies along with the development of reforming and clean-up systems are of utmost importance if hydrogen production is desired on-board ships.

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NOMENCLATURE

A	Slope of Tafel curve	Volt
E_o	Open circuit voltage	Volt
i_{den}	Load current density	mA/cm^2
LHV	Lower heating value	MJ/Kg.mole
m	Fuel cell voltage constant	Volt
$\dot{m}$	Mass flow rate	kg/s
n	Fuel cell voltage constant	cm^{2}mA^{-1}
P_C	Power of compressor	kW
P_E	Total power of expanders	kW
P_{par}	Parasitic power	kW
P_{P1}	Feed water pump power	kW
P_{P2}	Fuel cell cooling water pump power	kW
$P_{PEM,AC}$	Fuel cell output AC power	kW
r	Specific resistance	kΩcm^2
V_{cell}	Fuel cell voltage	Volt

Greek symbols

η_{Aux}	Auxiliary systems efficiency
$\eta_{DC/AC}$	DC / AC conversion efficiency
η_{FC}	Fuel cell efficiency
η_{FP}	Fuel processing efficiency
η_{HTS}	High temperature shift reactor efficiency
η_{LTS}	Low temperature shift reactor efficiency
η_{motor}	Electric motor efficiency
$\eta_{net.el}$	Net electric efficiency
η_{PEMFC}	Proton exchange membrane fuel cell efficiency
η_{PROX}	Preferential oxidation efficiency
η_{REF}	Reforming section efficiency
η_{SOFC}	Solid oxide fuel cell efficiency
$\eta_{Stack\ voltage}$	Stack voltage efficiency
η_1	POX inlet to total fuel feed efficiency

Abbreviations

AC	Alternating current
AF	Air to fuel ratio
DC	Direct current
ECAs	Emission Control Areas
HTS	High temperature shift reactor
H_2O	Water vapor
IMO	International maritime organization
LNG	Liquefied natural gas
LTS	Low temperature shift reactor
NO_x	Nitrogen oxides emissions
PEMFC	Proton exchange membrane fuel cell
PROX	Preferential oxidation reactor
ppm	Part per millions
REF	Reforming
SC	Steam to carbon ratio
SREF	Steam reforming
SOFC	Solid oxide fuel cell
SO_x	Sulfur oxides emissions
SREF-PEM	Steam reforming based proton exchange membrane fuel cell
SOFC-PEM	SOFC based reforming option for PEMFC
U_f	Fuel utilization coefficient
WGS	Water gas shift reactor

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