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Design and Thermodynamic Analysis of an SOFC System for Naval Surface Ship Application

Diesel-fueled fuel cell systems can be more clean and efficient energy solutions than internal combustion engines for electric power generation on-board naval surface ships. NATO Navy steam and gas turbine and diesel ships are powered by a naval distillate fuel (NATO symbol F-76). In this study, a 120 kW F-76 diesel-fueled solid oxide fuel cell system (SOFC) as an auxiliary engine on-board a naval surface ship was designed and thermodynamically analyzed. A diesel-fueled SOFC system was compared to diesel-electric generator set in a case naval surface ship. [DOI: 10.1115/1.4024254]

1 Introduction

The diesel engine has been a vital power in naval surface ships. Main propulsion and auxiliary diesel engines used on naval ships emit mainly CO_2, SO_2, NO_x, and hydrocarbons into the atmosphere. Exhaust gases are the primary source of emissions from naval ships. As pollution from merchant ships, the contribution of naval ships to air pollution has become more important. In 2002, US Naval Sea Systems Command, Ship Systems Engineering Station reported that emission contribution of worldwide naval shipping was 11% of global shipping. Global shipping makes a significant contribution to CO_2, SO_x, and NO_x emissions. As seen in the report of Endresen et al. [1], the emission of CO_2, NO_x, and SO_2 by ship corresponds to about 2–3%, 10–15%, and 4–9% of the global anthropogenic emissions, respectively. Diesel engine exhaust contains harmful pollutants in a complex mixture of gases and particulates. The exhaust from diesel engines is highly toxic. There are human health hazards associated with exposure to diesel engine exhaust. The hazards include acute exposure-related symptoms, chronic exposure related noncancer respiratory effects, and lung cancer. Ship emissions contribute to numerous adverse environmental impacts. Some of these are acidification, eutrophication of terrestrial and coastal ecosystems, damage to vegetation from ozone, deposition of toxic polycyclic organic matter, and visibility impairment and regional haze [2].

The International Maritime Organization (IMO) [3] reported that shipping was estimated to have emitted 1046×10^6 tonnes of CO_2 in 2007, which corresponds to 3.3% of the global emissions during 2007. International shipping was estimated to have emitted 870×10^6 tonnes or about 2.7% of the global emissions of CO_2 in 2007. Emissions from naval activities were not included in the second IMO GHG Study 2009. However, IMO [3] reported that contribution of naval shipping activities to the economy was $150,000 million in 1999 and $173,891 million in 2004. Twenty-seven percent of total operations and 13% of total cost in international shipping in 2004 were related to naval shipping. Today's conventional technology for auxiliary energy productions in ships has largely reached its potential for emission reductions. New and more energy efficient technologies are needed for a further decrease. One of those new technologies is fuel cell system. Fuel cells are a perfect choice for difficult marine applications such as ships. Unit cells form the core of a fuel cell and make the energy conversion available. These devices convert the chemical energy contained in a fuel electrochemically into electrical energy. The basic physical structure, or building block, of a fuel cell consists of an electrolyte layer in contact with an anode and a cathode on either side.

This study is intended to provide electric power generation on board of naval ships. In this study, a 120 kW F-76 diesel-fueled SOFC as an auxiliary engine on-board a naval surface ship has been designed and thermodynamically analyzed. In analysis, thermodynamic properties of real gases have been calculated using the Java program. The SOFC system has been compared to a diesel-electric generator set in a case surface naval ship.

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1.1 The Case Work: A Naval Surface Ship Auxiliary Power Production. The case naval surface ship has two marine diesel engines for auxiliary power production, each with engine power of 72 kW. The characteristics for a diesel generator on a naval ship are presented in Table 1. The air emission per functional unit, 1 kW h, is calculated and is shown in Table 2.

The International Maritime Organization, to reduce ship based air pollution in maritime and provide for continual improvement, issued MARPOL 73/2078/97 conventions. Appendix VI (Protocol 97) Prevention of Air Pollution from Ships entered in to force May 19, 2005. According to this protocol, the vessels have to apply the NO_x and SO_x standards of Appendix VI [4]. NO_x

Table 1 Specification of a diesel generator on a naval ship

Engine power	72 kW
Type	2-stroke, 6-cylinder
Speed	1200 rpm
Type of fuel	NATO F-76 diesel
Fuel consumption (at rated power)	20 kg/h
Generator power	60 kW
Nominal voltage	120 VDC
Nominal current	500 A
Mass	7500 lb (3400 kg)
Volume	115″ long × 40″ wide × 72″ tall (5420 l)

Table 2 Air emission factors for case auxiliary diesel engine

Component	g/kWh
CO_2	890
SO_x	0.75
NO_x	11.5
CO	0.5

emission limits are set for diesel engines, which range from 9.8 to 17 g/kW h depending on the engine maximum operating speed.

2 Hydrogen Energy and Fuel Cells and SOFC

Hydrogen is the lightest, the simplest, and one of the most abundant elements in nature. However, since it is not a free element, different production methods are required to extract pure hydrogen from its natural form using advanced technologies that are still in research and development stages. Fuel cells are energy conversion devices that produce electricity directly from a gaseous fuel electrochemical combination of the fuel with an oxidant. Among the currently available fuel cell technologies, SOFC are considered as the most promising options for marine applications. Hydrogen, for the operation of an SOFC, can be produced by means of the autothermal reforming of liquid hydrocarbons. An SOFC is an electrochemical device that converts chemical energy of a fuel and an oxidant gas (air) directly into electricity without irreversible oxidation. SOFCs are advanced electrochemical reactors operating at a high temperature and are presently under development for a variety of electric power generation applications with high energy conversion efficiency, and CO can actually be used as a useful fuel for SOFCs. When an external load is applied to the cell, oxygen is reduced at the porous air electrode to produce oxide ions. These ions migrate through the solid electrolyte to the fuel electrode, and they react with the fuel, H_2 or CO, to produce H_2O or CO_2. Alternatively, a proton conducting solid electrolyte can be used, where H_2 is oxidized to produce protons that subsequently react with oxygen to form water [5].The reactions occurring at the anode of an SOFC is

$$H_2 + O^{=} \rightarrow H_2O + 2e^- \quad (1)$$

$$CO + O^{=} \rightarrow CO_2 + 2e^- \quad (2)$$

The reaction occurring at the cathode is

$$\frac{1}{2}O_2 + 2e^{=} \rightarrow O^{=} \quad (3)$$

The overall reactions are

$$H_2 + \frac{1}{2}O_2 \rightarrow H_2O \quad (4)$$

$$CO + \frac{1}{2}O_2 \rightarrow CO_2 \quad (5)$$

SOFCs have an electrolyte that is a solid, nonporous metal oxide, usually Y_2O_3-stablilized ZrO_2. The cell operates at 600–1000 °C where ionic conduction by oxygen ions takes place. Typically, the anode is a Ni-ZrO_2 cermets and the cathode is Sr-doped $LaMnO_3$. The operating principle of a SOFC with an oxide ion conductor is schematically shown in Fig. 1.

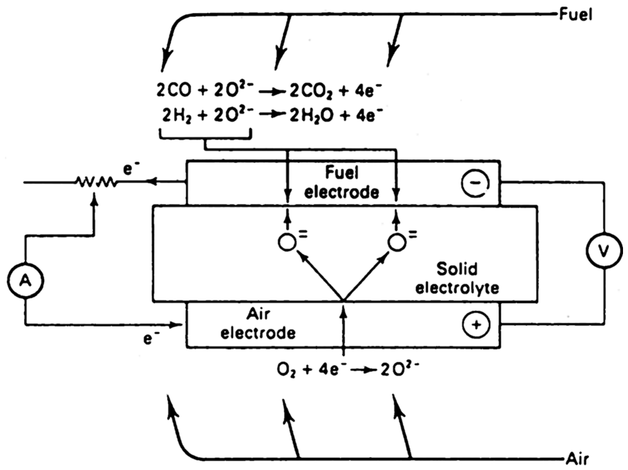

Fig. 1 Principle of operation of SOFC [5]

3 Choice of Fuel for SOFC Systems of Naval Surface Ships

Hydrogen is an ideal fuel for fuel cells because of its high reactivity and zero emission characteristics. However, it is not feasible to store the hydrogen in naval surface ships because of higher volume requirements, high fuel storage cost, and low energy storage efficiency and security problems. Diesel is one of the best hydrogen storage systems because of its very high hydrogen volumetric density (100 kg H_2 m^{-2}) and gravimetric density [6]. This makes diesel reforming an attractive option for hydrogen production on-board naval surface ships.

Table 3 Some properties of logistic fuel NATO F-76 [9]

Density, at 15 °C, kg/m^3 (max)	876
Distillation end point, °C (max)	385
Flash point, °C (min)	60
Viscosity, at 40 °C (mm^2/s)	1.7–4.3
Ash, wt. % max	0.005
Hydrogen content, wt. % (min)	12.5
Sulfur content, wt. % (max)	0.5

Power systems for the navies of NATO countries operate on naval distillate fuel (NATO symbol F-76). It is feasible to store naval distillate fuel instead of the hydrogen onboard naval surface ships. This fuel is characterized as a 385 °C (max) end boiling point diesel fuel with up to 1% sulfur by weight. By 2008, maximum sulfur content of fuel is 0.5 wt. % [7,8]. Some properties of NATO F-76 are shown in Table 3.

Desulphurization of the diesel fuel should be carried out to protect the catalysts of the reformers and fuel cells from sulfur poisoning. Both reforming catalysts and fuel cells require sulfur levels in fuels to be below 0.1 ppm. It was reported that testing at Fuel Cell Energy, Inc. with NATO F-76 distillate fuel containing 3800 ppm sulfur demonstrated the capability to achieve 0.1 ppm sulfur with hydrodesulfurization [10].

In another work, it was reported that the integrated diesel fuel processor, which is composed of an autothermal reformer, a desulfurizer, and a postreformer, was successfully operated for about 2500 h without significant degradations, and the overall system degradation rate was about 5%/2500 h. The autothermal reformer (ATR) catalyst was Pt on Gd-doped CeO_2 (CGO-Pt) and the post-reforming catalyst was Ru on CGO (CGO-Ru) [11]. Distillation characteristics of NATO F-76 diesel fuel, which are measured by us, are given in Fig. 2.

4 General SOFC System Design and Thermodynamic Analysis

In the case ship, a diesel-fueled SOFC system is designed to generate 120 kW electrical power. General system specifications are given in Table 4. The system will be operated at atmospheric pressure, and the flow resistance in the pipelines and system components is neglected. The diesel-fueled SOFC system consists of

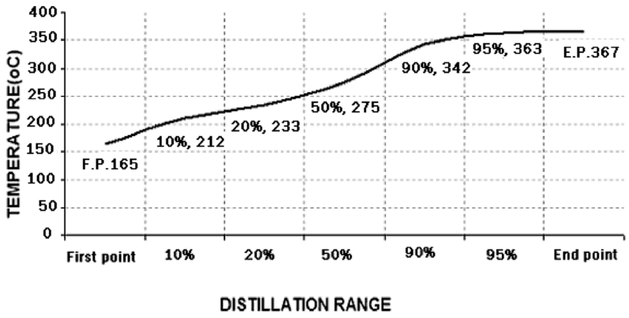

Fig. 2 A typical of distillation curve of NATO F-76

Table 4 General system properties

Type of fuel cell	SOFC
Net power	120 kW
Fuel type	NATO F-76 diesel
Type of reformer	ATR
Pressure	Atmospheric pressure + 0.1 bar
Fuel storage	Liquid diesel tank

an SOFC stack, an autothermal reformer, an anode off-gas burner (afterburner), fuel pumps, air supply, blowers, power electronics, a number of heat exchangers for heat integration, and additional balance-of-plant components. A steady state operation is assumed. Heat exchangers and blowers are assumed adiabatic.

4.1 Nominal Heat Balance. F-76 diesel fuel stored in the fuel tank of a ship is preheated and boiled. After the desulfurization step, the desulfurized fuel is mixed with steam, superheated, and flows to the autothermal reformer. The gases produced by the fuel reformer enter to the anode side of the SOFC and come in to reaction with oxygen in the air, which is sent to the cathode. After being used, gases coming from the anode and cathode are sent to the catalytic burner, and gases produced from the catalytic burner are sent to the high temperature heat exchanger to recover thermal energy. The diesel fuel is a complex mixture of many different hydrocarbons. The composition of the diesel fuel used in the study is given in Table 5.

Ideal gas approach can be used for most of thermodynamic fuel cell system analysis. But, since the process involves boiling of diesel fuel and heavy vapor representation, the ideal gas equation carries some error. Therefore, the Lee–Kesler equation, which is a modified Benedict–Webb–Rubin (BWR) equation, is used to calculate thermodynamic properties. The compressibility factor of a real fluid (diesel fuel) is related to the properties of a simple fluid ($w = 0$) and those of n-octane as a reference fluid. The nonideality of a gas is expressed by the compressibility factor Z:

$$Z = \frac{PV}{RT} \tag{6}$$

The compressibility factor Z for the fluid in the Lee–Kesler equations is calculated [12]

$$Z = Z^{(0)} + \left(\frac{w}{w^{(R)}}\right)\left(Z^{(R)} - Z^{(0)}\right) \tag{7}$$

where

$$Z^{(0)} = \frac{P_r V_r^{(0)}}{T_r} \tag{8}$$

$$Z^{(R)} = \frac{P_r V_r^{(R)}}{T_r} \tag{9}$$

Table 5 Fuel mixture exhibiting similar characteristic to NATO F-76 diesel fuel [9]

Component	Formula	Mole fraction	Mass fraction
n-Nonane	C_9H_{20}	0.01715	0.0122
n-Decane	$C_{10}H_{22}$	0.03079	0.0243
n-C11 (n-Undecane)	$C_{11}H_{24}$	0.05964	0.0517
n-C12 (n-Dodecane)	$C_{12}H_{26}$	0.09655	0.0912
n-C13 (n-Tridecane)	$C_{13}H_{28}$	0.1960	0.2007
n-C14 (n-Tetradecane)	$C_{14}H_{30}$	0.1780	0.1959
n-C15 (n-Pentadecane)	$C_{15}H_{32}$	0.08319	0.0980
n-C16 (n-Hexadecane)	$C_{16}H_{34}$	0.03902	0.0490
n-C17 (n-Heptadecane)	$C_{17}H_{36}$	0.01837	0.0245
n-C18 (n-Octadecane)	$C_{18}H_{38}$	0.00865	0.0122
n-C19 (n-Nonadecane)	$C_{19}H_{40}$	0.00409	0.0061
n-C20 (n-Eicosane)	$C_{20}H_{42}$	0.001978	0.0031
n-Pentilbenzen	$C_{11}H_{16}$	0.00328	0.0027
n-Hexilbenzen	$C_{12}H_{18}$	0.004556	0.0041
n-Heptilbenzen	$C_{13}H_{20}$	0.005626	0.0055
n-Oktilbenzen	$C_{14}H_{22}$	0.005495	0.0058
n-Nonilbenzen	$C_{15}H_{24}$	0.005206	0.0059
n-Decilbenzen	$C_{16}H_{26}$	0.005367	0.0065
n-C11benzen	$C_{17}H_{28}$	0.002328	0.0030
n-C12benzen	$C_{18}H_{30}$	0.001463	0.0020
Naftalen	$C_{10}H_8$	0.04248	0.0302
I-Metilnaftalen	$C_{11}H_{10}$	0.08293	0.0654
I-Etilnaftalen	$C_{12}H_{12}$	0.05228	0.0453
I-Propilnaftalen	$C_{13}H_{14}$	0.03410	0.0322
I-Bütilnaftalen	$C_{14}H_{16}$	0.02103	0.0215

$$w^{(R)} = 0.3978 \tag{10}$$

Pressure-volume-temperature relations and thermodynamic properties such as enthalpies, heat capacities, viscosities, thermal conductivities for 25 pure components, and mixtures have been estimated. The Lee–Kesler equation has been used for real pure gases and their mixtures. Thermodynamic specifications have been calculated and stability of energy provided for every point (29 points) in the fuel cell system. Thermodynamic specifications are provided by using Java software language [13]. Nominal heat balance has been carried out for 1 kmol diesel fuel.

An F-76 diesel-fueled SOFC system auxiliary power unit flowsheet diagram is shown in Fig. 3. The energy balances at the cell, the reformer, and the afterburner are presented by the following equations:

$$\text{Cell}: \sum_{\text{in}} \dot{n}_i \bar{h}_i + \dot{Q}_{\text{cell}} = \sum_{\text{out}} \dot{n}_i \bar{h}_i + \dot{W}_{FC,DC} \tag{11}$$

where $\dot{Q}_{\text{cell}} = 0$ for a system with an external reformer.

$$\text{Reformer and after burner}: \sum_{\text{in}} \dot{n}_i \bar{h}_i = \sum_{\text{out}} \dot{n}_i \bar{h}_i \tag{12}$$

where $\dot{n}_i$ and h_i represent the molar flow rate and specific molar enthalpy of the flow stream into and out from each component in the system.

An increase of adding water can slightly increase H_2 yields by water gas shift (WGS) reaction and can suppress the coke formation. But, more heat energy would be consumed for vaporizing the water at higher H_2O/C. In addition, SOFC voltage decreased with H_2O/C due to H_2O dilution.

4.2 Autothermal Reformer. There are three major reforming technology options for producing hydrogen-rich fuel cells. Feeds from fuels: steam reforming (SR), partial oxidation (POX), and autothermal reforming. The more dynamic and energy-efficient ATR process is hence considered advantageous over SR and POX for transportation applications. Autothermal reforming

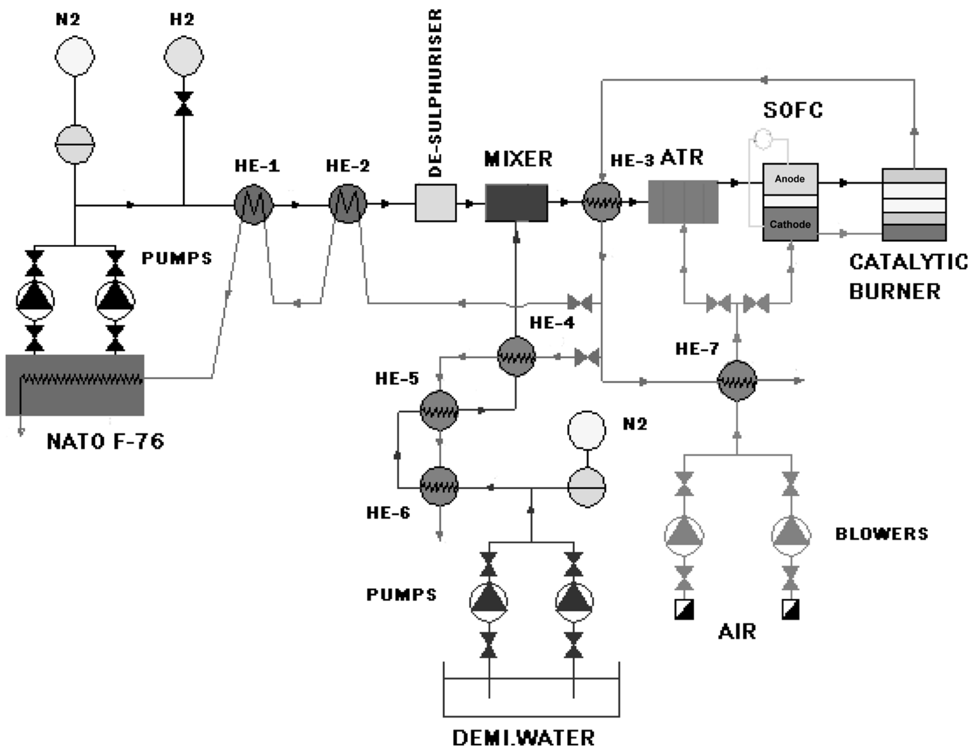

Fig. 3 F-76 diesel-fueled SOFC system auxiliary power unit

is a combination of partial oxidation and steam reforming. The fuel is mixed with steam and substoichiometric amounts of oxygen or air where the ratios of oxygen to carbon (O:C) and steam to carbon (S:C) are properly adjusted so that the partial combustion supplies the necessary heat for endothermic steam reforming. The autothermal reformer consists of two zones: the thermal zone or the partial oxidation zone where partial combustion occurs and the heat generated is supplied to the subsequent endothermic steam reforming occurring in the catalytic zone. The reactions can either be run in a single reactor or in separated reactors that are in good thermal contact. The autothermal reformers combine the heat effects of the POX and SR reactions by feeding the fuel, water, and air together into the reactor [14].

$$\text{Fuel}\left(C_nH_mO_p\right) + \text{air} + \text{steam} \rightarrow \text{carbon oxides} + \text{hydrogen} + \text{nitrogen}, \quad (\Delta H_r < 0) \tag{13}$$

The ratio of the amount of water given to the reactor to the amount of carbon in fuel is an important parameter for the fuel reformer. This parameter is called the steam-carbon ratio. For a high fuel reforming efficiency, steam to carbon ratio should be low, but in this reaction carbonization (formation of solid carbon) should be eliminated. This will require a relatively high steam to carbon ratio. In our design, autothermal reaction temperature is taken as 700 °C, in which the reaction enthalpy is zero and steam to carbon ratio is taken as 3.5. At the exhaust of autothermal fuel reformer, we will assume that the mixture will reach a chemical equilibrium state. Chemical equilibrium calculation is carried out by using HSC Chemistry Ver. 1.10 software. The product gas compositions of ATR for diesel can be thermodynamically calculated as functions of temperature based on the principle of Gibbs free energy minimization. ATR product gas composition for 1 kmol diesel fuel is given in Table 6.

4.3 Solid Oxide Fuel Cell Stack. The SOFC is the main part of this energy exchanger system. In this system, air is provided by a fan and then heated through a heat exchanger. Heated air is sent to the cathode of the fuel cell and further heated and deoxygenated. The depleted air exhaust is sent back to the heat exchanger to heat incoming streams. Hydrogen rich fuel created in the fuel reformer is sent to the anode of the fuel cell, and electrical and thermal energy is created in the fuel cell. Anode-supported SOFCs with Ni-yttria-stabilized zirconia (YSZ) anode were fabricated and studied using H_2–CO syngas fuels in Ref. [15]. SOFC operating parameters are presented in Table 7. It is impossible to use all fuel in real systems. The percentage of fuel used in fuel cell is called fuel changing rate. In our design, fuel cell input temperature is 700 °C, fuel cell output temperature 850 °C, and fuel reforming rate is assumed as 90%. At the fuel cell anode side, for 1 kmol F-76 diesel fuel, input and output mole rates are given in Table 8.

Table 6 ATR product gas composition

Reformate gas	kmol/kmol diesel
H_2	26.086
CO	4.3922
N_2	14.290
H_2O	31.413
CO_2	8.5549

Table 7 Operating parameters [15]

Parameter	Value
Operating voltage	0.80 V
Current density	400 mA/cm^2
Power density	300 mW/cm^2
Elektrolit	YSZ
Anode	Ni-YSZ
Cathode	LSM
Electrolyte	YSZ

Table 8 Inlet and exit mole rates of SOFC anode

Gas	Inlet (kmol/kmol diesel)	Exit (kmol/kmol diesel)
H_2O	31.413	54.8904
H_2	26.086	2.6086
N_2	14.290	14.290
CO	4.3922	0.43922
CO_2	8.5549	12.5078

Table 9 Inlet and exit of catalytic burner

GAS	Inlet (kmol/kmol diesel)	Outlet (kmol/kmol diesel)	g/kW h
H_2O	54.8904	57.499	769
H_2	2.6086	0	0
N_2	164.766	164.766	3432
CO	0.43922	0	0
CO_2	12.5078	12.947	423
O_2	26.285	24.760	589

4.4 Catalytic Burner. As mentioned in Sec. 4.3, some of the fuel at fuel cell anode exhaust will remain unused. A catalytic burner is used to burn the remaining fuel from the anode side with the surplus air from the cathode side. Due to small percentages of fuel in the gas stream, it is difficult to burn in classical chambers. A catalytic burning system is suitable for relatively lean mixture combustion. Platinum in the catalytic reactor will provide the required activation energy for combustion. Gas inlet and exit mole percentages of the catalytic combustion unit are given in Table 9. Catalytic burner exhaust is also exhaust of the fuel cell system. For this reason for comparison of exhaust emission values these mole percentages are also listed as g/kW h bases.

4.5 Heat Exchangers. Energy is transferred by using gas, which is provided from the combustion chamber with fuel, water, and heat exchanger. System includes a total of seven heat exchangers. It has been used shell and tube heat exchangers for gas-liquid fluids and compact heat exchangers for gas-gas fluids. Austenitic stainless steel (UNS S30403) for three heat exchangers exposed to mid-degree temperature (up to 750 °C), and nickel based alloy (UNS N06625) [16,17] for four heat exchangers exposed to high temperature (over 750 °C) has been chosen.

4.6 Air Supply. The system uses two of the same blowers for air supply. Air is needed for both the autothermal reformer and cathode section of the SOFC. Also, the air supply blowers are vane-type compressors driven by an electrical motor, the rotational speed of which is controlled by a frequency converter. In the study, one redundant air blower has been used to increase the system reliability. The blower efficiency is an important factor for the overall system efficiency. For the air supply, an overall efficiency of 72% is used.

4.7 Power Electronics. Power electronics is necessary to convert the electric power supplied from SOFC to the required grid voltage. The SOFC delivers direct current (DC). We have no inverter because the ship service electric voltage is 120 VDC. Figure 4 shows power conditioning for different cases for SOFC electric power output.

5 Results and Comparison

In the ideal case of an electrochemical converter, such as a fuel cell, the change in Gibbs free energy ΔG of the reaction is available as useful electric energy at the temperature of the conversion. The ideal efficiency of a fuel cell, operating reversibly, is then

$$\eta_{\text{ideal}} = \frac{\Delta G}{\Delta H}, \quad \eta_{\text{ideal}} = 77.03\% \tag{14}$$

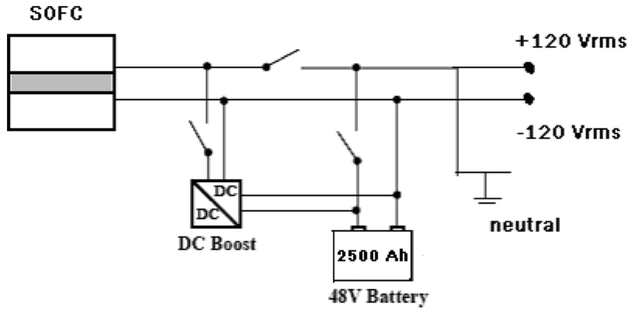

Fig. 4 Power conditioning for SOFC electric power output

Table 10 SOFC system results

Parameter	Value
Total electric power, kWe	120
Reformer type	ATR
Reformer S/C	3.5
Fuel cell inlet gases (% mol)	
Hydrogen (H_2)	30.78
Carbon monoxide (CO)	5.18
Nitrogen (N_2)	16.86
Water (H_2O)	37.07
Carbon dioxide (CO_2)	10.10
Reformer efficiency, %	85.0
SOFC efficiency, %	68.47
Net efficiency, %	55.28
Total F-76 diesel feed required, kg/h	30

The thermal efficiency of an actual fuel cell operating at a voltage of V_{cell} is 68.47%. The fuel processor efficiency based on the lower (net) heating value (LHV) of the component was determined using

$$\eta_{\text{fuel processor}} = \frac{\text{LHV}(\text{H}_2 + \text{CO})_{\text{out}}}{\text{LHV}(\text{Fuel})_{\text{in}}} \tag{15}$$

The gross efficiency, which combined the fuel cell and fuel processor was 58.19%.

$$\eta_{\text{gross}} = \varepsilon_{\text{fuel cell}}\varepsilon_{\text{fuel processor}}, \quad \eta_{\text{gross}} = 68.47\% \times 85\% = 58.19\% \tag{16}$$

The net efficiency of an SOFC system with F-76 diesel fuel, estimated as 55.28, included the effect of the parasitic energy load on the system required to power the pumps and blower.

5.1 Comparison of SOFC and Diesel Generator. Total fuel consumption is 30 kg/h, for producing 120 kW electrical powers. For the case naval surface ship, to produce the same amount of power with the existing two piece diesel generator, the consumption is a total of 40 kg/h F-76 diesel fuel. Using a solid oxide fuel cell system in place of a diesel generator, fuel consumption will reduce 10 kg/h F-76 diesel fuel. Results of thermal analysis of an SOFC system and comparison of SOFC system and marine diesel engine is given in Tables 10 and 11, respectively. Figure 5 presents the amount of diesel fuel needed as a function of an SOFC system power.

For production of 120 kW electric powers, it has been designed as in 170 mm × 170 mm dimensions, total 1350 fuel cells, and

Table 11 Comparison of SOFC system and marine diesel engine

Criteria	Diesel fueled SOFC system	Marine diesel engine (2 engines)
Net power	120 kWe	120 kWe
Net efficiency	55.28%	25.29%
Total fuel consumption	30 kg/h	40 kg/h
Emission (CO_2)	423 gCO_2/kW h	890 gCO_2/kW h
Mass	520 kg	3400 kg
Volume	2000 l	5420 l
Noise level	50 dB (A)	100 dB (A)

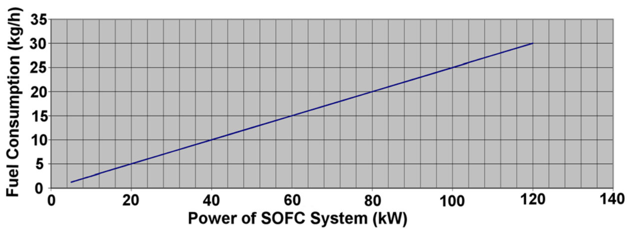

Fig. 5 Consumption of NATO F-76 fuel

two stacks. Each of them includes 75 serial plates, which are composed of nine cells. It has been found that an SOFC system will be 520 kg and 2000 l. Two diesel generator sets are 6800 kg and 10,840 l. There is not any weight or place restriction for fuel cell stacks, and on surface ship, they can be installed as modular. A diesel-fueled SOFC system emits only 423 g CO_2/kW h, and 52, 47% less than a diesel auxiliary engine. In the case ship, diesel motor's NO_x emission is more than the limits of MARPOL Annex VI (10,898 g/kWh NO_x, at $n = 1200$ rpm). Noise level in the engine room of the case war ship was measured 100 dB (A). Motional parts are only blower and pumps in SOFC system. Blower noise level is 70 dB (A). Furthermore in the SOFC system, the noise of the blower can be decreased to 50 dB (A) by insulating. The case ship's service electric is direct current. Therefore, an inverter is not needed for changing the current to AC. Moreover, total installation cost of the SOFC system was decreased and 5% efficiency drop is prevented by not using the inverter. For comparison, the calculated electrical efficiency for NATO F-76 diesel-fueled fuel cell system based on steam reforming and PEM-fuel cells was 35–40%, depending on the current density of the fuel cell applied [18]. Their simulations were at lower operating temperatures.

6 Conclusions and Future Work Recommendations

The 120 kW F-76 diesel-fueled SOFC system as an auxiliary engine on-board a naval surface ship was designed and thermodynamically analyzed. The SOFC system was compared to a diesel-electric generator set in a case naval surface ship. One of the challenges of fuel cell applications on naval surface ships is the capability of using fossil fuel instead of pure hydrogen. It has been anticipated that naval distillate fuel will be a long-term solution for fuel cell application onboard naval ships. This solution requires a fuel reformer to extract hydrogen from naval distillate fuels. With excellent emissions performance, the diesel-fueled SOFC system secures not only the IMO/MARPOL regulations but also assures more of what the regulation needs. Noise scale is logarithmic, so a difference of 10 dB (A) make a significant difference to the human ear. Therefore, the noise in a cabin of a fuel cell powered ship is expected to be similar to that found in an office. With a diesel-fueled SOFC system, new and stricter environmental regulations can be observed. Furthermore, it provides minimized signatures for naval ships. The desulphurization must reduce the sulfur content to the required level of the reformer. Therefore, in further developments in the next years, desulphurization units, sulfur-tolerant autothermal reformers, and anode materials for SOFC application will need to be investigated.

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