

DEVELOPMENT OF A COMBINED CYCLE OF SOLID OXIDE FUEL CELL AND MICRO GAS TURBINE FOR MARINE POWER SYSTEMS

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ABSTRACT

Fuel cell is an energy conversion system providing almost zero pollution, with a high energy conversion efficiency, flexibility and no noises of operation. In a fuel cell, the chemical energy incorporated in the fuel is converted directly into electricity and heat. A solid oxide fuel cell (SOFC) discharges high temperature exhaust gases in which the thermal energy can be extracted for electricity generation by the use of micro gas turbines (MGT). This paper presents development of a marinised SOFC-MGT combined power system, including modelling of SOFC electrochemical, fuel (methane) reformer, thermal, power conditioning unit (inverter) and MGT. The SOFC based power system uses a stack consisting of 20 tubular SOFC cells connected in series. It provides 2.5kW output of electricity power and 2.5kW heat energy which drives the MGT. Different SOFC and MGT coupling methods with relevant calculations have been investigated. Matlab-Simulink® software is used for the modelling and simulation of the combined SOFC-MGT system.

Keywords: fuel cell, SOFC, fuel reforming, MGT, power conditioning unit, marine engine.

NOMENCLATURE

A: surface area, m^2
 C_p : specific heat at constant pressure, J/kg K
 C_v : specific heat at constant volume, J/kg K
D: diameter, m
E: reversible potential of a cell, V
 E_0 : standard (Nernst) potential, V
F: Faraday constant, 96487 C/mol
 Δh : specific enthalpy change of reaction, J/mol
 $\Delta \dot{H}$: enthalpy change of the control volume, J/mol
I: current, A
i: current density, A/m^2
 i_0 : exchange current density, A/m^2
K: reaction constant
l: current flow distance, m
m: DC/AC inverter modulation index
 \dot{m} : mass flow rate, kg/s
p: partial pressure, Pa
 \dot{Q} : heat transfer, kW
R: gas constant, 8.3143 J/(mol K), or resistance, Ω .
T: temperate of control volume, K
 U_f : fuel utilization rate.
V: voltage, v, or volume, m^3
W: work, J or kJ
w: work of control volume, J or kJ
 η_{act} : activation losses, J/mol
 η_{conc} : concentration losses, J/mol
 η_{Ω} : Ohmic losses, J/mol
X: line reactance, Ω

Greek Letters

Γ : pre-exponential factor
 σ : Stefan-Boltzmann constant, $5.67 \times 10^{-8} W m^{-2} K^{-4}$
 ε : emissivity

Subscripts

a: anode
c: cathode
ast: air supply tube

ele: electrochemical reaction
i: i^{th} item of gas species
j: value of gas species
ise: isentropic
r: methane reforming
s: shift reforming or solid control volume
t: micro gas turbine

1. INTRODUCTION

Facing the increasingly stringent anti-pollution policies of the world, it is more and more difficult for the traditional marine diesel engines to meet the emission standards at national and international levels. On one hand, engine designers and engine users try to improve the combustion quality of diesel engines which will increase the costs of engine and managements. On the other hand, the shipping companies have to invest money focusing on the engines' exhaust treatments through all kinds of physical and /or chemical methods. At the same time, most SOFC research programs are currently targeting the development of stacks and systems for land use, and almost all ships, including large commercial vessels are still using diesel engines which bring out the pollutions and low efficiency compared to fuel cell systems. Our project is trying to develop a new type of power system which combined a 5 KW SOFC fuel cell system with a micro gas turbine system to get marinised SOFC-MGT power for commercial ships. Through the former part of the system, electrical power can be generated directly consuming natural gas and the latter part of the system, from the discharged thermal energy (exhaust gas) can be reused to get more electrical power and thus the whole system's efficiency increased further.

2. SOFC SYSTEM MODEL

2.1 TUBULAR SOFC SYSTEM DESCRIPTION

A 5kW SOFC-MGT hybrid system (shown in Figure 1) is developed under the basis of a 5 KW SOFC fuel cell (Siemens tubular fuel cell) system which produces 2.5KW electricity and 2.5KW heat energy respectively. In this tubular SOFC fuel cell system, Methane 9 (Natural gas) is reformed in reformer 1 which is transported from the valve 5, 7 and desulfurizer 6, then the hydrogen (reformed from natural gas in 1) flows through the outside of the cell 2 and oxygen from inside where chemical reaction happened and electrical current produced with high temperature exhaust gases 16 discharged. There is a combustor near the igniter 17 where excessive hydrogen and part of incoming natural gas burn to get more energy for gas turbine and also keep the SOFC stack at appropriate temperature. The air is blown to a container 22 and distribute to the inside of air supply tube ast 3 (shown in Figure 1 and 2). At the end of air supply tube, the incoming air back flows to the inside of cell 2 to react with the hydrogen outside. The isopentane rankine cycle system has been adopted to generate more electrical power through the heat exchanger 11 instead of a direct coupling of gas turbine.

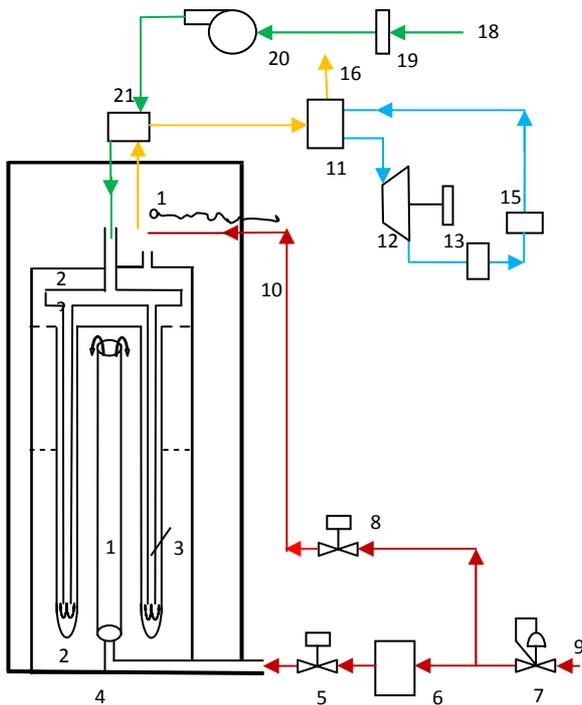


Figure 1: 5kW SOFC and Micro Gas turbine hybrid system

1-Reformer 2-Cell 3-Air Supply Tube 4-Fuel Cell Stack 5-Flow Control Valve 6-Desulfurizer 7-Regulator 8-Flow Control Valve 9-Natural Gas 10-To Combustor 11-Heat Exchanger 12-MG Turbine 13-Generator 14-cooler 15-Compressor 16-Exhaust Gas Exit 17-Igniter 18-Air 19-Air Filter 20-Air Blower 21-Heat Recuperator 22-Air container

2.2 SOFC INTERNAL REFORMING MODEL

The following assumptions are made for the reforming model in developing the SOFC system:

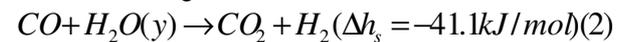
- . All gases are assumed to be ideal gas and no gas phase reactions.
- . All exterior walls are adiabatic. There is no heat exchange between cells and no gases leak outside the system.
- . Gas distribution is uniform and no variation of the gas distribution among cells.
- . One-dimensional behavior along the stream direction is assumed as well.

The function of reforming is to convert the methane into hydrogen and this is necessary due to large amount of hydrogen is difficult to get directly in nature and storage of hydrogen is also not easy to deal with, especially on ships. In this reforming process, the following reactions are taking place between and among the cells:

Methane reforming:



Shift reforming:



Electrochemical reaction:



Where x, y and z are the conversion rates (molar flow rate) of CH_4 , CO , and H_2 , respectively. Assuming that the above reactions are always in equilibrium and the equilibrium constant can be calculated from the partial pressures of equations (1) to (3) as:

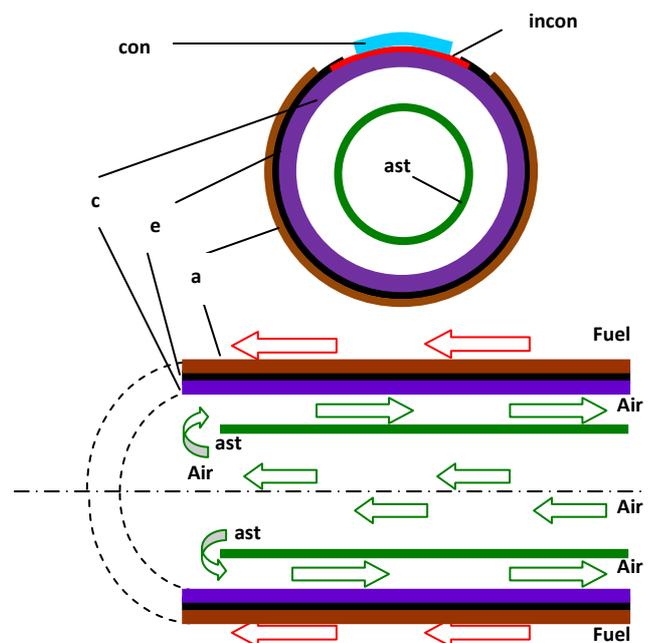


Figure 2: Schematic diagram of tubular SOFC cell
a-Anode-Brown; ast-Air Tube-Green; c-Cathode-Purple; e-Electrolyte-Black; con-Interconnection Contact-blue; incon-Interconnector-Red

$$K_r(T) = \frac{P_{H_2}^3 P_{CO}}{P_{CH_4} P_{H_2O}}$$

$$= \frac{\frac{CO^{in} + X - Y}{n^{in} + 2x} * \frac{(H_2^{in} + 3x + y - z)^3}{(n^{in} + 2x)^3}}{\frac{CH_4^{in} - x}{n^{in} + 2x} * \frac{H_2O^{in} - x - y + z}{(n^{in} + 2x)^3}} P_{cell}^2$$

(4)

$$K_s(T) = \frac{P_{H_2} P_{CO_2}}{P_{CO} P_{H_2O}}$$

$$= \frac{\frac{CO_2^{in} + y}{n^{in} + 2x} * \frac{(H_2^{in} + 3x + y - z)}{n^{in} + 2x}}{\frac{CO^{in} + X - Y}{n^{in} + 2x} * \frac{H_2O^{in} - x - y + z}{(n^{in} + 2x)^3}}$$

(5)

$$z = U_F * (\dot{n}_{H_2, in} + 3x + y) \quad (6)$$

Where superscript 'in' is inlet; 'n_{in}' is total inlet molar flow rate of natural gas and steam.

The equilibrium constants of reforming process are temperature dependant and expressed as follows:

$$\log K(T) = AT^4 + BT^3 + CT^2 + DT + E \quad (7)$$

Table 1: Equilibrium constant of methane reforming and shift reforming

A	B	C	D	E
-2.63E-11	1.24E-07	-2.25E-04	1.95E-01	-6.61E+01
5.47E-12	2.57E-08	4.64E-05	3.93E-02	1.32E+01

At a stable state, it can be assumed that methane reforming reaction has been driven to totally completion (National Energy Technology Laboratory, 2002), plus the known temperature, Kr and Ks can be calculated using the equation (7) and table 1. Once U_f, Kr, Ks are known, x, y and z can be calculated. For transient simulation, the T dependant function has to be solved out by using the energy balance equations of the controlled volume. According to the energy conservation law, the general equations can be expressed as following:

$$\Delta\dot{H}_{in} + \Delta\dot{Q}_{gen} = \Delta\dot{H}_{out} + V_{cell} I$$

(8)

$$\Delta\dot{Q}_{gen} = -(x\Delta h_r + y\Delta h_s + z\Delta h_{H_2}) + I^2 \sum R_i$$

(9)

$$\Delta\dot{H}_{in} = (\sum_i \dot{m}_i c_{pi})(t_{in,a} - t_0) + \dot{n}_{H_2O, in, a} h_{H_2O}(t_{in,a}, y_{H_2O} P_{in, a})$$

$$+ (\sum_i \dot{m}_i c_{pi})_{in, c} (t_{in, c} - t_0)$$

(10)

$$\Delta\dot{H}_{out} = (\sum_i \dot{n}_i c_{pi})_{in, c} (t_{out} - t_0) + \dot{n}_{H_2O, out, a} h_{H_2O}(t_{out}, y_{out})$$

(11)

$$I = 2\dot{n}_{H_2} F$$

(12)

$$\Delta h_{H_2} = T\Delta S = T(S_{H_2O}^0 - S_{H_2}^0 - \frac{1}{2}S_{O_2}^0) - \frac{R}{2} \ln(\frac{P_{H_2} P_{O_2}}{P_{H_2O}^2})$$

(13)

Here, $\Delta\dot{Q}_{gen}$, $\Delta\dot{H}_{in}$, $\Delta\dot{H}_{out}$ means net heat generated, molar rate energy inlet, outlet energy respectively and fuel cell current determined by equation (12). Also, $\Delta h_r, \Delta h_s, \Delta h_{H_2}$ means specific enthalpy difference generated by methane reforming, shift reforming and electrochemical reaction respectively. By solving this complicated equations from (4) to (13), x, y and z can be theoretically calculated.

2.3 ELECTROCHEMICAL MODEL

The tubular SOFC fuel cell which firstly designed by Siemens Westinghouse has been adopted here to develop the hybrid system. The cell parameters are listed in table 2. Here, the electrochemical model will be briefly summarized in order to clarify some of the results discussed in the followings sections. Considering the Nernst potential and the irreversible concentration loss η_{conc} , activation loss η_{act} and ohmic resistance loss η_{Ω} (all in volts), the actual voltage of the fuel cell can be expressed as:

$$V = E_0 + \frac{RT}{2F} \ln \frac{P_{H_2} P_{O_2}^{1/2}}{P_{H_2O}} - \eta_{act} - \eta_{conca} - \eta_{concx} - \eta_{\Omega}$$

(14)

Table 2: SOFC geometrical parameters

	Outer diameter	Thickness	Length
Air inducting tube	0.012	1*10 ⁻³	1.450
Anode	0.022	1*10 ⁻⁴	1.5
Cathode	0.02172	2.2*10 ⁻³	1.5
Electrolyte	0.0218	4*10 ⁻⁵	1.5
Inter connection	1/8 of perimeter	8.5*10 ⁻⁵	1.5

Where $E_0 = \frac{-\Delta g_f^0}{2F}$ is the standard potential which

almost lineally changes with temperature (Bossel, 1992) and can be expressed as:

$$E_0 = 1.26485 - 2.4727 \times 10^{-4} T - 1.875 \times 10^{-8} T^2 \quad (15)$$

The activation losses can be calculated by Butler-Volmer equation:

$$\eta_{act} = \frac{2RT}{n_e F} \sinh^{-1} \left(\frac{i}{2i_0} \right) \quad (16)$$

Where, i_0 exchange current density is a function of local species concentration and temperature at both the cathode and anode (Chan et al, 2001):

$$i_{0,a} = \gamma_a \left(\frac{p_{H_2}}{p_{ref}} \right) \left(\frac{p_{H_2}}{p_{ref}} \right) \exp \left(-\frac{E_a}{RT} \right) \quad (17)$$

$$i_{0,c} = \gamma_c \left(\frac{p_{O_2}}{p_{ref}} \right)^{0.25} \exp \left(-\frac{E_c}{RT} \right) \quad (18)$$

$$\eta_{conc} = \frac{RT}{n_e F} \ln \left(\frac{1}{x_{O_2}^0} - \left(\frac{1}{x_{O_2}^0} - 1 \right) \exp \left(\frac{iRT}{2n_e F D_{ef,c} p} \right) \right) \quad (19)$$

$$\eta_{conc,a} = \frac{RT}{n_e F} \ln \left(\frac{1 - \frac{iRt_a}{2FD_{ef,a} p x_{H_2}^0}}{1 + \frac{iRt_a}{2FD_{ef,a} p x_{H_2}^0}} \right) \quad (20)$$

Where pre-exponential factors, exponents a, b, c and activation energies are taken from tests by Costamagna and Honegger. Both γ_a and γ_c are the charge transfer coefficients. The concentration

losses can be calculated through the equations applying Fick's law (Sanchez, et al)

The ohmic losses can be calculated on the basis resistance of the cell and Ohm's law which the related equations are: $\eta_{\Omega} = R_{\Omega} i$ and $R_{\Omega} = \rho l / A$

Here l stands for current flow length which is also the thickness of each layer; A represents the unit area and ρ resistivity of material respectively. The resistivity for anode, cathode, electrolyte and interconnection are functions of temperature as indicated by Campanari and Lora (2004) and Jiang et al (2006).

2.4 SOFC THERMAL MODEL

Large amount of heat exchange continuously flows with high exothermic and endothermic reactions in and out of the SOFC cells. Before start the thermal modelling, we need make the following assumptions as well:

□. Heat only release from electrochemical reactions, electrical resistance and these generated heat partly supply for methane reforming and shift reforming, partly to heat the incoming air and fuel, plus the solid parts inside the stack which keep the stack in a proper temperature range.

□. Heat transfer between solid part and gas or steams, occurs mainly by convection heat transfer. The heat transfer between solid parts (cell and ast) by radiation should be considered. Radiation heat transfer between solid parts and gas or steams is neglected.

- . The cell voltage at each element is equivalent.
- . Heat exchange between cells is not considered.

According to assumptions above, the net generated heat can be evaluated by electrochemical reactions and equations on (9), (12) and (13):

As showed in figure 2, the thermal exchange happens among solid parts (cell and ast), solid parts and gases or steams, plus gas flowing in and out with corresponding heat energy exchanges. So, the whole controlled volume can be divided into five parts as: air in the ast; ast; air between ast and cell; cell; fuel of the exterior cell. Based on the above assumptions, detailed heat transfer will be: the heat transferred by convection including: from air of exterior ast to ast $Q_{cv-air-ast}$ and from ast to its interior air $Q_{cv-ast-air}$; from cell annulus to the its interior air (exterior ast air) $Q_{cv-ce-air}$ and the cell to fuel $Q_{cv-ce-fu}$; Heat transferred by radiation from the cell to ast is $Q_{rad-ce-ast}$; heat exchanges due to air and fuel (including H_2 , H_2O) flowing are $Q_{air-flow-ast}$, $Q_{air-flow-ce}$, and $Q_{fu-flow}$. The corresponding general equations can be expressed as below:

Each solid control volume has an energy conservation equation:

$$m_s c_p \frac{dT}{dt} = \sum \dot{Q} - \sum \dot{W}_{out} = \dot{Q}_{net}$$

(21)

$$\text{Here, } \Delta \dot{Q}_{net} = \sum \dot{Q}_{in} - \sum \dot{Q}_{out} - W$$

For the cell part:

$$\begin{aligned} \Delta \dot{Q}_{net} = & \Delta \dot{Q}_{gen} - \dot{Q}_{cv-ce-fu} - \dot{Q}_{cv-ce-air} - \\ & \dot{Q}_{rad-ce-ast} - \dot{Q}_{air-flow-ce} - \dot{Q}_{fu-flow} \end{aligned}$$

(22)

For the heat transfer of convection from solid control volumes to fuel or air, Newton's law can be utilized as:

$$\dot{Q}_{cv} = Ah(T_2 - T_1)$$

(23)

Where, A is heat flow area and the heat transfer coefficient h can be given by the Nusselt expression as:

$$h = N_u k_c / D_h$$

(24)

4. RESULTS, DISCUSSION AND CONCLUSION

The cell voltage and current density relationship at various temperatures for the operating pressure of 1atm is illustrated in Fig.3. The simulation result shows that it normally has a better voltage performance at higher temperature. Figure 4 shows the cell over potential at the operating temperature of 1000°C and pressure of 1atm. it can be seen that all the three kind of losses rise as the current density increases. According to the discussion in Al-Sulaiman et al., the net electrical energy efficiency decreases as the current density increases. This reduction in the energy efficiency is because of the decrease in the cell voltage as the current density increases and eventually less power output derived from the SOFC system.

For the micro gas turbine (MGT), based on the input parameters shown in table 3 and the parameters (3.5kpa, 250°C, 800l/min) of exhaust gases being provided, two types of designs are considered.

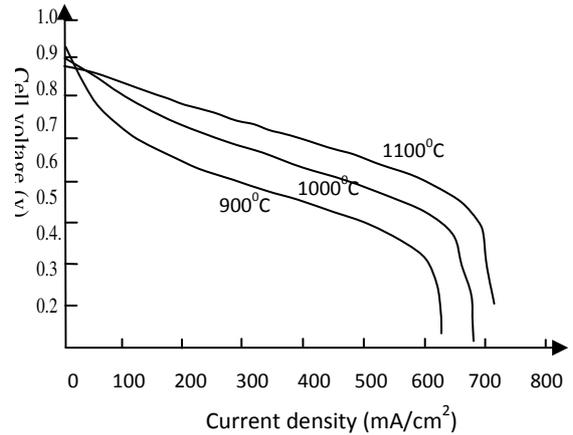


Fig 3: Effect of operating temperature on the cell voltage (p=1atm)

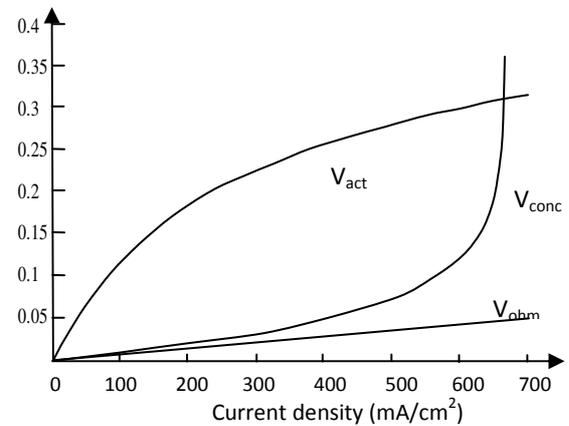


Fig 4: Effect of operating temperature on the cell overpotential (loss) (p=1atm)

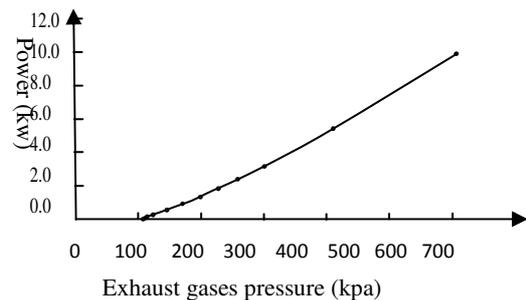


Fig 5: Gas turbine output power changes with the inlet pressure

The simplest one is use the exhaust gases to drive both a turbine and the coaxial electrical generator directly. This first choice of calculation results shown on figure 5, we can get the conclusion that the gas turbine input pressure greatly affect its power output and under the ambient input pressure

(3.5kp above the atmospheric pressure), only very small amount of electrical power generated (40.1w, in the pre-mentioned condition). So this method, the MGT efficiency is very low and this result is also shown by F.A. Al-Sulaiman et al which the net electrical energy efficiencies increase as the turbine inlet pressure increases. Further analysis of flow rate and temperature parameters, we will see that as the flow rate and working temperature increased, the more gas turbine power output also can be generated obviously. From this point of view, for the practical ship power supply, we can design the pressurized and large power output (flow rate) SOFC fuel cell system, choose the appropriate temperature and this will benefit the micro gas turbine power output and hence increase the whole system supply power and efficiency as well.

Table 3: The SOFC fuel cell input and related parameters

Input parameters	value
Maximum fuel flow rate	1.2 m ³ /h
Stack Fuel utilization rate (%)	0.74
Fuel input temperature	25 °C
Maximum air flow rate	72 m ³ /h
Air input temperature	43.5 °C
Stack temperature	975°C
Fuel cell operating pressure	1 atm

Another type of design considered and adopted here is using an organic system to drive the turbine and generate electrical power which is shown in figure1 (blue line). Using the isopentane steam as the system working medium, heat source parameters, pressure 3.02 Mpa, temperature 180°C and flow rate, 0.00238 kg/s, are selected and the pressure and temperature drop to 0.129Mpa, and 65°C after expansion (cooling water parameter: 20°C, 3m pressure head and 0.065655kg/s flow rate), the turbine overall power output is 127 watts. Hence, more electrical energy will be generated by this type of design compare to the direct coupling method. But the cost will go up due to the complexity of the Rankine cycle system.

In all, a 5 KW SOFC-MGT hybrid marine power system fed with natural gas has been developed. The SOFC electrochemical and thermal model, plus energy based performance analysis is carried out in this paper. Further different kind of micro gas turbine coupling methods and their corresponding performances have been discussed.

It can be concluded that it is possible to combine micro GT and SOFC fuel cell technology to develop a marinised SOFC-MGT power system and provide propulsion and/or auxiliary power for ships. Because the SOFC sub system has a high electricity efficiency, plus micro GT 'reproduce

'more electricity which makes the whole system efficiency increases to 60 percent possible, it is time for us to try to develop the real SOFC based system to replace currently used traditional engines on ships.

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