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Design, modelling and simulation of a hybrid fuel cell propulsion system for a domestic ferry

Ameen M. Bassam[1,2)], Alexander B. Phillips[3)], Stephen R. Turnock[1)], and Philip A. Wilson[1)]

[1)]Fluid Structure Interactions Group, University of Southampton, UK
[2)]Naval Architecture and Marine Engineering Department, Port Said University, Egypt
[3)]National Oceanography Centre, Natural Environment Research Council, UK

Abstract

It is proposed to install a hybrid fuel cell electric propulsion system on a domestic ferry. The fuel cell hybrid system is compared with the existing diesel propulsion system for this ferry using a developed time-domain three-degree of freedom ship simulator implemented in the MATLAB/Simulink environment. Performance comparison of the two systems is made in terms of first cost, fuel cost, system weight and volume. Simulation results for the ship are validated using real ship operational data for the existing diesel propulsion system. The developed ship simulator can be used for further studies of fuel cell hybrid propulsion systems and thus can help ship system designers in investigating different system lay-outs and different energy management strategies of hybrid fuel cell propulsion systems.

Keywords

Hybrid Power Systems; Fuel Cell; PEMFC; Battery; Ship Simulator; MATLAB/Simulink.

Introduction

World trade handled by shipping has been continuously growing, consequently reducing shipping's negative environmental impact has been an area of great concern. With over 80% of the world trade by volume handled by shipping (UNCTAD, 2013), both the world fleet number and average size of ships are increasing that results in greater fossil fuel consumption and associated air pollution.

A recent study by the International Maritime Organization (IMO) estimates that shipping in 2012 emitted 949 million tonnes of CO_2, which is about 2.7% of the global emissions during 2012. In the absence of new emission reduction policies, mid-range emissions scenarios show that by 2050, CO_2 emissions from international shipping may increase by 50% to 250% with reference to emissions in 2012 (Smith et al., 2015). Moreover, compared to other transport modes, shipping has the highest SO_2 emissions due to fuel sulphur content (Eyring et al., 2005).

In order to limit ships green house gases (GHG) emissions, the IMO has introduced the Energy Efficiency Design Index (EEDI), the Ship Energy Efficiency Management Plan (SEEMP), the Energy Efficiency Operational Indicator (EEOI) and emission control areas (ECA) where ships must use fuels with sulphur content less than 0.1% (Buhaug et al., 2009).

A number of EEDI and SEEMP measures have been published by the Marine Environment Protection Committee (MEPC) to help ships comply with the existing legislation which includes the use of hybrid electric power and propulsion systems. These systems combine the prime movers with an energy storage system which can result in reduction of fuel consumption and ship emissions (Dedes et al., 2012; Dedes, 2013). In order to increase the potential of hybrid systems in reducing energy demand and ship emissions, fuel cells could be used as a main source of power in these systems (Bazari and Longva, 2011; Díaz-de Baldasano et al., 2014). Fuel cells have high efficiency and power density, low noise and emissions, and electricity is its output which makes it a promising candidate for use in hybrid electric systems (Pukrushpan et al., 2004; Wang et al., 2011).

In this work we consider a $123m$ domestic ferry for which the effectiveness of a suitably sized hybrid fuel cell electric propulsion system is compared to the ferry conventional diesel propulsion system. Numerical simulation plays an important role in the design of hybrid fuel cell propulsion system because of the large cost of real testing and the lack of a proper testing facility. Moreover, the behaviour of the ship and its propulsion system can be foreseen and analysed using numerical simulations. Therefore, a time-domain three-degree of freedom (DOF) total ship simulator implemented in MATLAB/Simulink environment is developed in this study and used as a tool to simulate the performance of the ferry existing diesel system and calculate the required installed power. The results are then used to design the proposed hybrid fuel cell/battery system by sizing its components and compare it to the conventional diesel propulsion system in terms of: system weight, size, first cost and fuel cost as well.

Detailed set of the ferry operational performance data, which is readily available at (Smyril, 2016), is used to validate the simulation results of the ferry existing diesel propulsion system in order to show any variation of the real data with the simulation results.

Vessel & Voyage Description

This study uses the domestic ferry *'M/S Smyril'* owned by Strandfaraship Landsins as a case study and its main specifications are shown in Table 1.

Table 1. Specifications of the M/S Smyril ferry

Length	123 m
Breadth	22.7 m
Draft	5.6 m
Block coefficient	0.55
Passenger capacity	975
Car capacity	970 m / 200 cars
Service speed	21 kn
Main engines	4 * MAN B&W 7L32/40
Propeller diameter	4.3 m

The ships works around the Faroe Islands which is a sulphur emission control area from the capital Tórshavn to the southernmost island Suduroy as shown in Figure 1 sailing two or three trips each day and the duration of each trip is less than 2 hours.

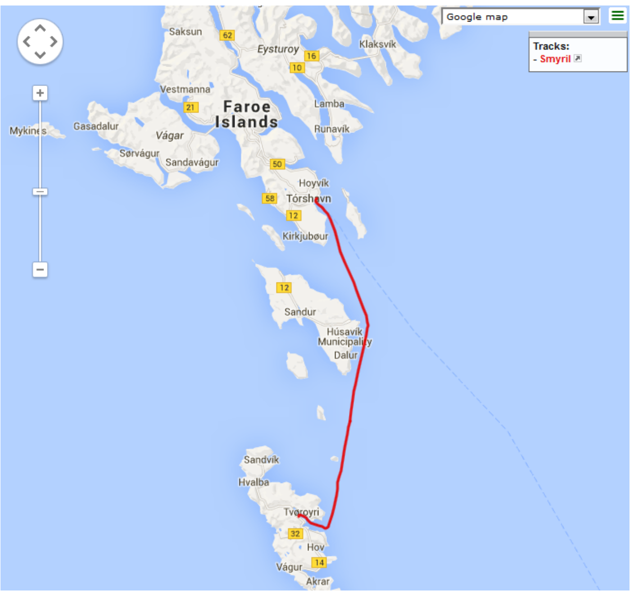

Figure 1. Ship voyage route created at GPSVisualizer.com

The examined ferry is equipped with four four-stroke diesel engines for propulsion driving two propellers through two gearboxes as shown in Figure 2. Propeller speed is around 140 rpm as reported by the ship owner company which corresponds to an engine speed of about 700 rpm with a specific fuel consumption of 186 g/kWh.

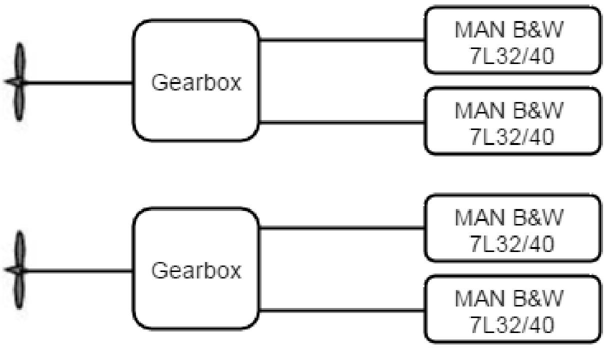

Figure 2. Configuration of M/S Smyril diesel propulsion system

Proposed System Description

The proposed hybrid fuel cell/battery propulsion system will consist of proton exchange membrane fuel cell (PEMFC) which is considered as the most promising fuel cell type to be used in transportation applications (Wang et al., 2011). The PEMFC modules are connected to the DC bus using a DC-DC converter to control its voltage while the battery system will be connected directly to the DC bus in order to power the DC motor through the motor controller as shown in Figure 3 using off-the-shelf components where possible.

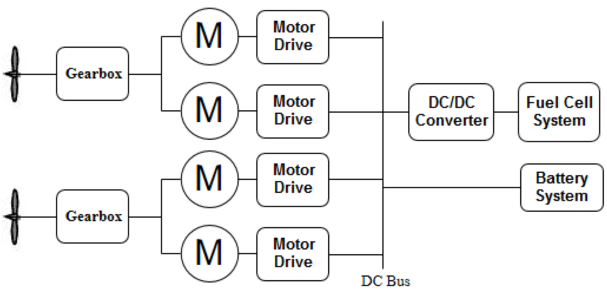

Figure 3. Proposed hybrid fuel cell propulsion system

Both the existing diesel engine propulsion system shown in Figure 2 and the proposed hybrid fuel cell/battery system shown in Figure 3 are included in the developed ship simulator to be compared for the same examined voyage shown in Figure 1.

Ship Simulator

The developed time-domain three DOF ship simulator is based on a building block modular approach where ship hull, propeller, rudder and different parts of the propulsion system are represented by separate submodels using MATLAB/Simulink environment which facilitate the modelling process. As shown in Figure 4, the ship simulator consists of a number of blocks where each block performs a certain calculation or represents a certain component of the system.

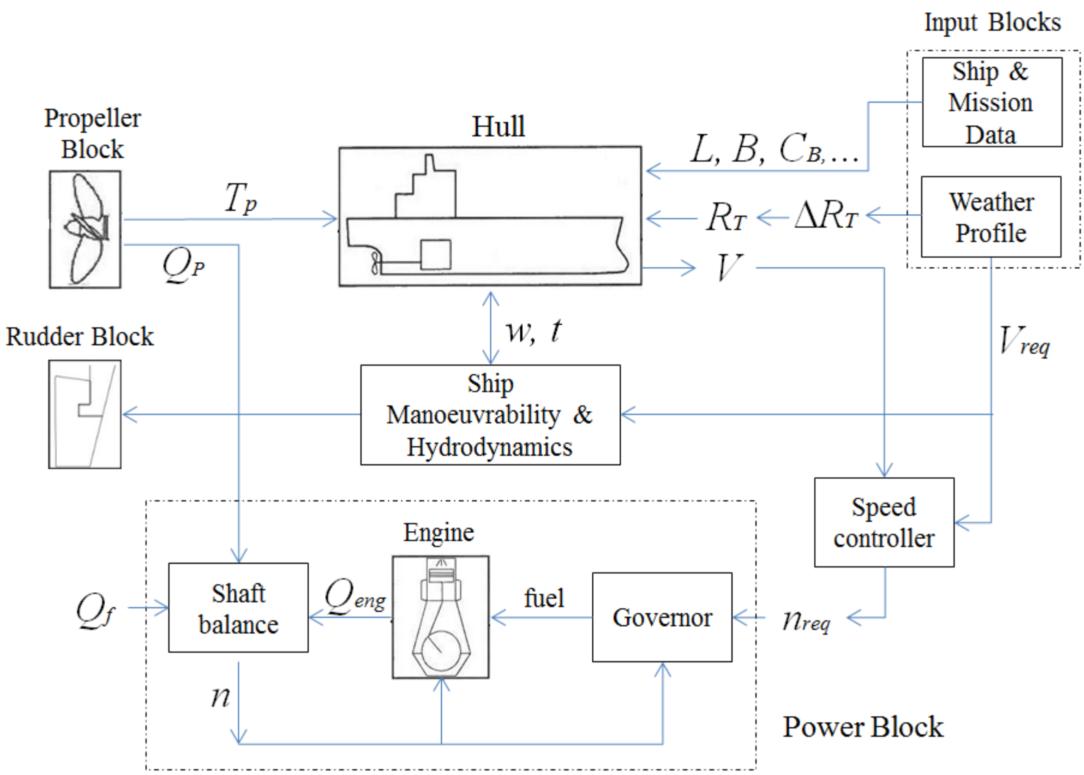

Figure 4. Total ship simulator representation using diesel propulsion system

Input Blocks

Data about the ship, its mission and route are provided through the input blocks in order to perform the required simulations. Data about the ship such as its dimensions and form coefficients, data about the mission such as the required speed (V_{req}) or the required rotational speed (n_{req}) and data about the route such as wind speed and direction. This data is then fed to the adjacent blocks automatically through the appropriate output ports.

Ship Resistance Blocks

These blocks contain the governing equations that define the ship interaction with the surrounding environment in terms of calm water resistance R_T and added resistance due to wind and waves $\triangle R_T$. Ship resistance can be predicted experimentally, numerically, or using an empirical/statistical approach. For preliminary estimates, regression analysis equations can be used and implemented directly in the simulation environment. In this work, Hollenbach regression analysis equations are used to calculate ship calm water resistance because of its wide range of application, relatively modern database, ease of programming and it requires fewer inputs than other methods such as Holtrop-Mennen (Molland et al., 2011).

For added resistance due to wind calculations, (Blendermann, 1994) has derived mathematical expressions for the prediction of wind loads on ferries from the statistical analysis of wind tunnels experimental results. Compared to Isherwood, Gould, and OCIMF, Blendermann experimental work is more reliable and comprehensive (Haddara and Soares, 1999) therefore, it is used in this work. For added resistance due to wave, (ITTC, 2005) recommends the use of Kreinter useful formula to estimate the increase in resistance due to the effect of waves with heights up to $2m$ as follows

$$\triangle R_T = 0.64 H_w^2 B^2 C_B \gamma / L \quad (1)$$

where H_w is the wave height, B is the ship breadth, C_B is the ship block coefficient, γ is water specific weight and L is the ship length.

Ship Hydrodynamics Block

As the hull interacts with the propeller, this block is responsible for estimating this interaction in terms of wake fraction w and thrust deduction t. Estimation of wake fraction and thrust deduction is important as it affects the propulsive efficiency and the propeller thrust and torque. Approximate formula based on regression analysis of experimental data can be used during preliminary design therefore, for twin screw ships, wake fraction is calculated using Taylor's formula (Molland et al., 2011) and thrust deduction is calculated according to (Holtrop and Mennen, 1982).

Propeller Block

This block inputs are the outputs of the previous blocks which are wake fraction, thrust deduction, ship speed and propeller speed and dimensions. The main outputs of the propeller block are the propeller thrust T_P and torque Q_P

calculated as a function of non-dimensional thrust K_T and torque coefficients K_Q as follows

$$T_P = K_T.\rho.n_p^2.D_p^4$$
$$Q_P = K_Q.\rho.n_p^2.D_p^5 \quad (2)$$

where ρ is water density, n_p and D_p are the propeller speed and diameter. The non-dimensional thrust and torque coefficients are calculated using the interpolation polynomials fitted for Wageningen B-screw series (Molland et al., 2011).

Manoeuvrability Block

Most of models that deal with total ship systems in the literature are limited to one DOF manoeuvring model where ship speed is calculated in surge direction only (Schulten, 2005). In order to have more real representation of ship performance during voyages, a three DOF manoeuvrability mathematical model developed by the Manoeuvring Modelling Group (MMG) is used (Ogawa and Kasai, 1978). The model three DOF are surge, sway, and yaw and its basic equations of motions are shown below

$$m\dot{u} - mvr = X$$
$$m\dot{v} + mur = Y \quad (3)$$
$$I_{zz}\dot{r} = N - x_G Y$$

where, X, Y, and N are hydrodynamic forces and moment acting on midship from the hull, propeller, and the rudder, x_G: the location of ship centre of gravity from the midship in x-axis, u and v are the component of ship speed in x and y direction, r: rate of turn, m: ship mass, and I_{zz}: moment of inertia of yawing where the ship center of gravity is the origin.

Power Block

Modelling of diesel engines has attracted much attention in recent years as it is used by the majority of ships. There are many models of diesel engines in the literature with different levels of complexity. Therefore, suitable diesel engine model should be selected based on the requirements of the simulation. In the context of conceptual design stage, a transfer function model of diesel engine can be used to provide the relation between shaft speed and the generated torque through the fuel pump index. As the examined ferry is equipped with four four-stroke diesel engines, a transfer function model of a four-stroke diesel engine is implemented in MATLAB/Simulink as shown in Figure 5.

The main input of this model is the required rotational speed n_{req} which is compared with the current rotational speed n and the difference between them is converted into a signal sent to the fuel pump where $\tau_{1..6}$ are time constants for the speed governor, actuator and diesel engine. The output of this model is the engine torque Q_{eng} which is then used with the propeller torque to calculate the current rotational speed as follow

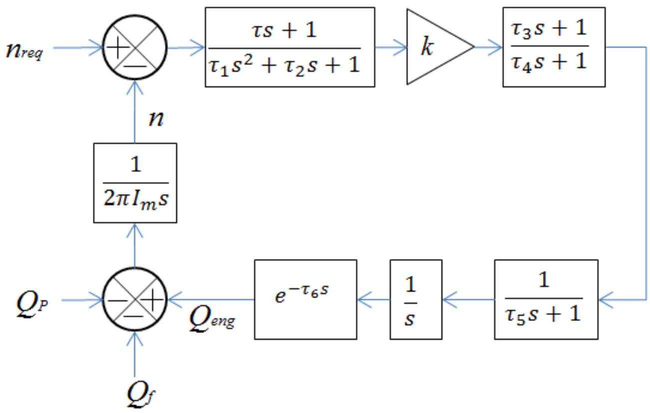

Figure 5. Diesel engine dynamic model

$$2\pi I_m \dot{n} = Q_{eng} - Q_P - Q_f \quad (4)$$

where I_m is the inertia of the rotating parts including the propeller and added inertia of the water and Q_f is the friction torque.

In order to assess the effectiveness of hybrid fuel cell propulsion systems, the power block contains as well a model of the proposed hybrid system which contains: DC motor & Controllers subsystem, fuel cell & DC-DC converter subsystem, battery subsystem, and an Energy Management Strategy (EMS) subsystem as shown in Figure 6.

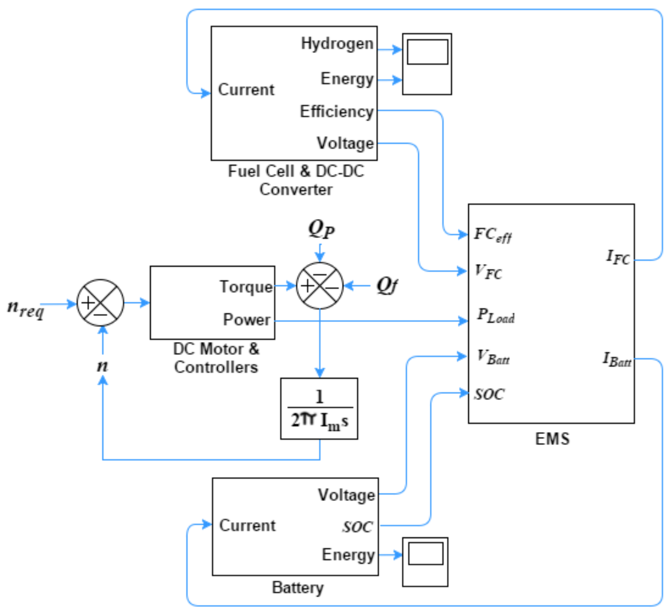

Figure 6. Hybrid fuel cell/battery propulsion system in Simulink/MATLAB environment

For hybrid fuel cell propulsion systems, the proper split of the required power P_{Load} between the fuel cell and the battery is a challenging problem which requires a suitable EMS. As illustrated in Figure 6, the EMS converts the required load P_{Load} into current and splits it to fuel cell current I_{FC} and battery current I_{Batt}. The main inputs to the EMS subsystem are battery state of charge

(SOC), battery voltage V_{Batt}, fuel cell efficiency FC_{eff}, and voltage V_{FC}.

The dynamic behaviour of the hybrid fuel cell systems is controlled through the EMS, which affects the system size, weight, efficiency and fuel consumption. Different energy management strategies have been proposed for hybrid fuel cell propulsion systems with different objectives. The objectives of EMS include low hydrogen consumption, low stress on the components, high fuel cell efficiency, high overall efficiency of the system, low storage system size, low cost, and long life cycle (Motapon et al., 2014).

EMS based on the classical proportional-integral (PI) controller has been proposed recently because of its simplicity and ease of tuning therefore, it is used in this study. The PI EMS allows the fuel cell to provide a steady power which reduces stresses on it and increase its lifetime. Meanwhile, the battery power is decided based on the difference between the reference value of the battery SOC and its current value as shown in Figure 7. The reference battery SOC is recommended by the automotive industry designers to be 60% (Fadel and Zhou, 2010).

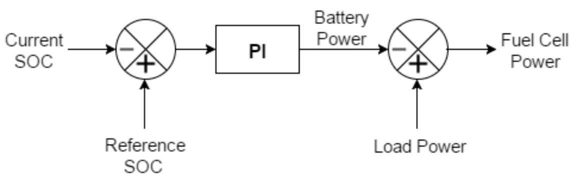

Figure 7. Classical PI control energy management strategy

Different types of electrical motors can be used for propulsion however, DC motor is selected because of its wide range of speed and torque, smooth running capability, low cost and less complex control system (Gupta et al., 2012). The motor controller efficiency is assumed to be 95%.

The used PEMFC mathematical model in this study is developed and validated in (Njoya et al., 2009) and it is implemented in Simulink as shown in Figure 8.

An unidirectional DC-DC converter is used with the PEMFC to regulate its voltage. The efficiency of the DC-DC converter is assumed to be 95% as well (EG & G Technical Services, 2004).

Moreover, the power block contains a mathematical model of a battery which is considered as the main energy storage device for transportation applications. The battery mathematical model is validated as well against experimental results in (Tremblay and Dessaint, 2009) and it is implemented in Simulink as shown in Figure 9.

Simulation Results

By using the ship geometrical particulars, data of the main engine and propeller and rudder angles, the developed ship simulator is used to simulate the ship performance during its normal voyage shown in Figure 1.

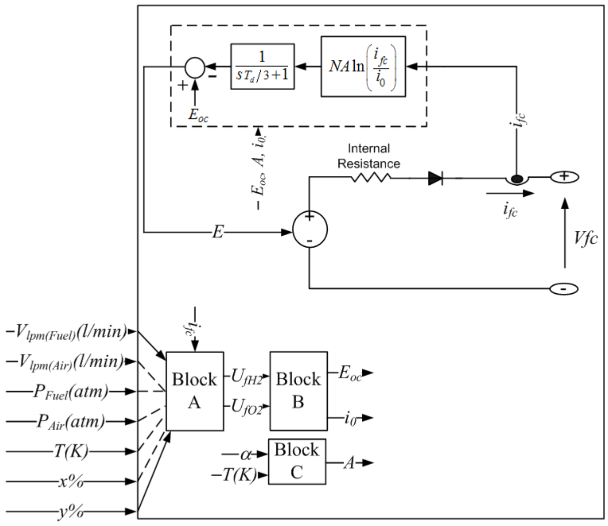

Figure 8. Fuel cell model in Simulink/MATLAB environment

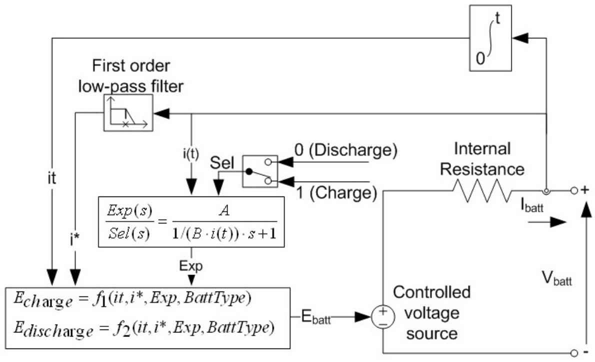

Figure 9. Battery model in Simulink/MATLAB environment

For almost two months from 16/2/2010 to 12/4/2010, the operational data was recorded onboard this ship and this data was made available online to encourage ship's benchmarking (Smyril, 2016).

Three different voyages of the same examined route have been extracted and used to validate the simulation results. As shown in Figure 10, simulation results of the ship speed are in good agreement with the real ship operational data for the three voyages.

Fuel consumption volume flow rate simulation results are also in good agreement with the real operational data except for the stopping phase of the voyage which includes reverse operation of the propellers which couldn't be captured by the developed simulator accurately as can be seen in Figure 11. The error between the simulation results and the real fuel consumption is about 5%. This is considered reasonable given the level of uncertainty in the modelling assumptions and acceptable as a basis for comparison.

The normal voyage time is less than 2 hours, however, it may take longer as shown in Figures 10 and 11. Simulation results include the forces acting on the ship hull

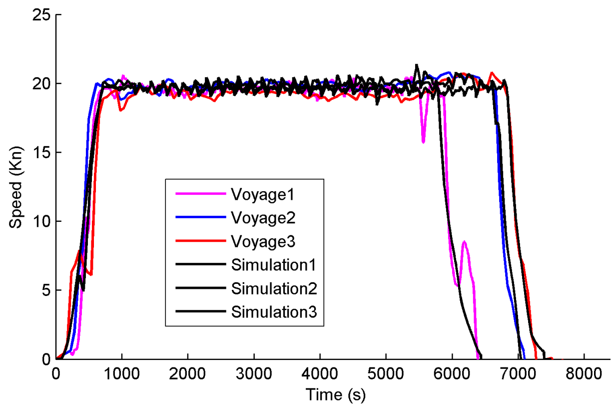

Figure 10. Validation of ship speed simulation result

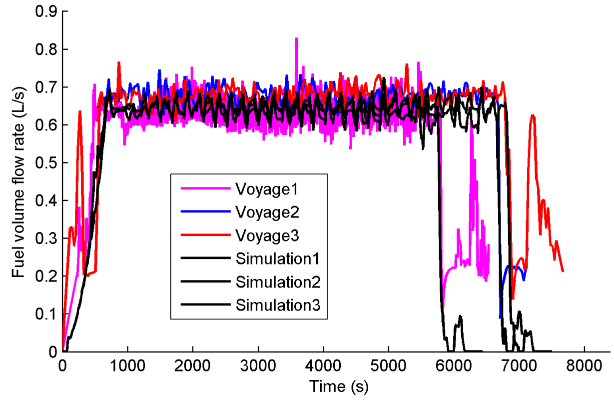

Figure 11. Validation of ship fuel volume flow rate simulation result

which include calm water resistance, added resistance and propeller thrust as shown in Figure 12 for voyage1.

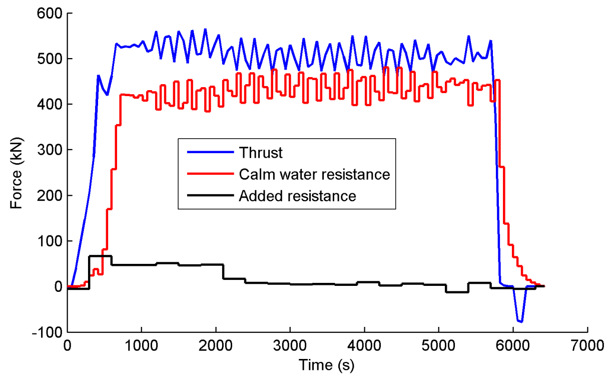

Figure 12. Acting forces on the hull during voyage1

A breakdown of the power consumed during voyage1 also can be presented using the developed ship simulator which allows the analysis of ship's performance and its propulsion system as shown in Figure 13.

The brake power developed by the engines is the highest which is transmitted through the shaft and gearbox to the propeller. Because of the shaft efficiency, the brake power is reduced and becomes delivered power. The propeller uses the developed power to generate the thrust power which is less than the delivered power because of

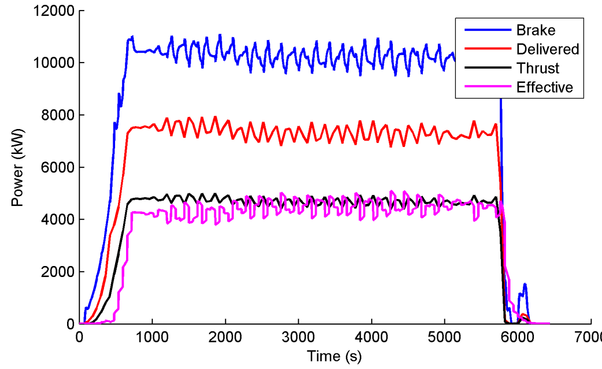

Figure 13. Consumed power breakdown during voyage1

the propeller efficiency. The effective power is also calculated as a function of calm water resistance and ship speed.

The consumed brake power during the voyage as shown in Figure 13 can be used to select the required sizes of the fuel cell and battery of the hybrid system. It is generally accepted that the fuel cell system provides the average required power while the battery system is charged or discharged if the required power is less or higher than the average required power supplied by the fuel cell (Shih et al., 2014).

The average consumed brake power is about 10300 kW as shown in Figure 13 which will be supplied from 158 fuel cell modules with a nominal power of 72 kW after taking the efficiencies of the motor controller and DC-DC converter into consideration. The fuel cell type is $NedStackPS50$ and its main specifications are shown in Table 2.

Table 2. Specifications of NedStack PS50 module

Net rated nominal power	50-72 kW
Output voltage	630 V
Efficiency	55-57 $\%$
Mass	600 kg
Volume	0.672 m^3
Expected life	20,000 h
First cost	235.51 $\$/kW$ (James et al., 2014)

Moreover, three lithium-ion battery packs of 500 Ah capacity will be used as a supplement to the fuel cell system and its main features are shown in Table 3. The distribution of the required power between the fuel cell system and the battery system is controlled using the PI EMS as described earlier.

As shown in Figure 14, the fuel cell system provides the average required power while the battery system provides power during acceleration.

During acceleration, the battery C-rate is high but it doesn't exceed its maximum value of 2.5C. Then, the PI EMS maintains the battery state of charge (SOC) during voyage and starts to charge the battery at low load phase

Table 3. Lithium-ion battery pack specifications (Alibaba, 2016)

Standard capacity	500 Ah
Output voltage	600 V
Standard C-rate	0.2C
Maximum C-rate	2.5C
Mass	2800 kg
Volume	2.29 m^3
First cost	1000 $\$/kWh$ (Ovrum and Bergh, 2015)

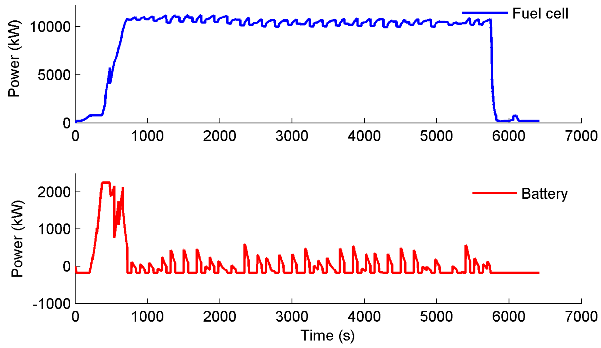

Figure 14. Fuel cell and battery power for voyage1

as shown in Figure 15. Later, the battery is recharged to its initial SOC after the voyage ends using power from the fuel cell system or a shore-shared (shore-side) system. A normal battery SOC of 70% is chosen as an initial value and 60% is the SOC reference value as recommended by the automotive industry designers.

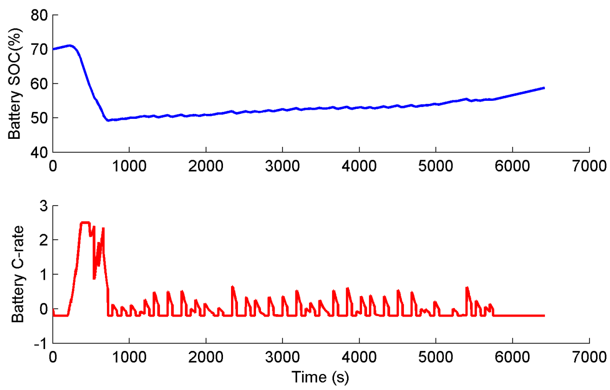

Figure 15. Battery SOC and C-rate for voyage1

In order to have a fair comparison between the proposed hybrid fuel cell system and the conventional diesel system, hydrogen storage, which is a main challenge, should be considered. Hydrogen can be stored mechanically, chemically or using adsorption materials and it has been considered as an alternative fuel for marine applications because of its clean carbon footprint and its high energy density per mass. In this study, hydrogen is assumed to be stored as a cryogenic liquid in a tank as suggested in (Veldhuis et al., 2007) for a catamaran. Tank capacity is 4000 kg_{H_2} which is sufficient for the daily operation of the examined vessel. The main specifications of the hydrogen tank is shown in Table 4.

Table 4. Liquid hydrogen tank specifications (Yang and Ogden, 2007)

Capacity	4000 kgH_2
Gravimetric density	0.142 kgH_2/kg
Volumetric density	70.8 kgH_2/m^3
Cost	$650,000

After taking the hydrogen tank and electric motors into consideration, the total weight and volume of the proposed hybrid fuel cell system are less than the weight and volume of the diesel engines as shown in Figure 16. Hybrid fuel cell system weight and volume saving percentages are 10% and 21% respectively compared to the conventional diesel propulsion system. However, the first cost of the hybrid system is higher than the diesel system by about 77% as shown in Figure 17.

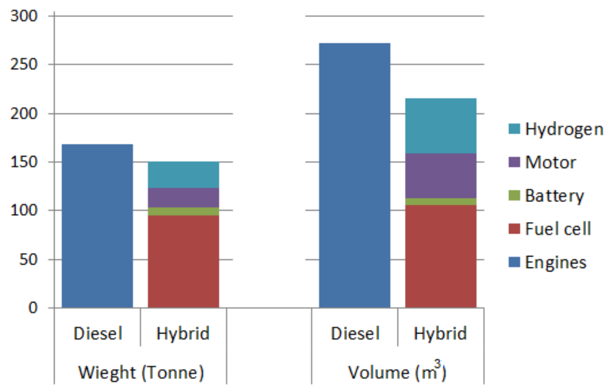

Figure 16. Proposed system weight and volume comparison

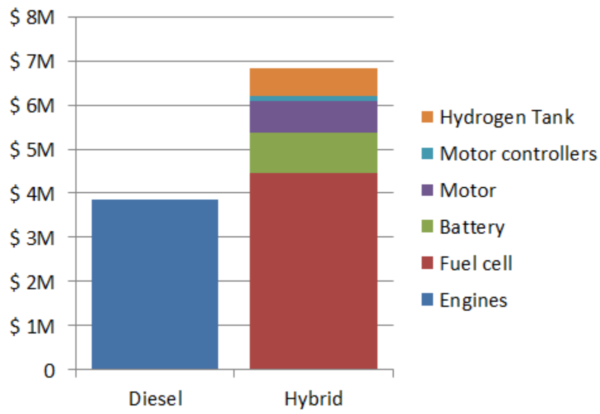

Figure 17. Proposed system first cost comparison

Moreover, the hydrogen fuel price is higher than diesel fuel which makes the operational cost of the hybrid fuel cell system higher than the conventional diesel system. However, using hydrogen as a fuel results in less emissions and a saving in the environmental damages caused by using diesel fuel which can be converted into cost saving as follows (Lutfi and Vezirolu, 1991)

$$D_{env} = E_n C_p \qquad (5)$$

where D_{env} is the cost of environmental damage, E_n is the energy consumption, and C_p is the environmental damage cost. As oil price has been dropping recently, ship fuel cost is reduced and the economic pressure is increasing on the clean energy investment. However, the environmental damage caused by fossil fuel costs more than the fuel cost as shown in Figure 18.

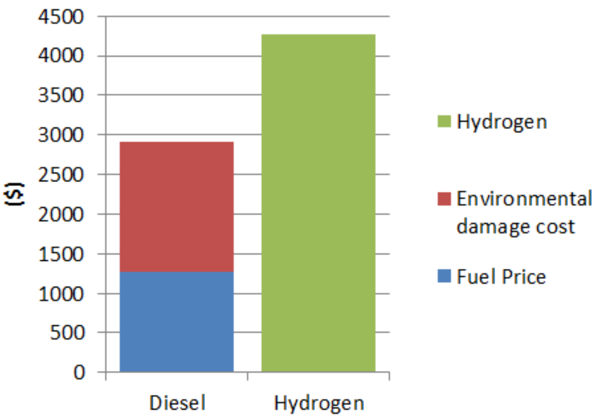

Figure 18. Fuel cost comparison for the examined voyage

Without taking the environmental damage cost into consideration, hydrogen has more than two-fold increase in the cost than marine diesel oil for the examined voyage. However, by taking the environmental damage cost into consideration, hydrogen cost is higher than marine diesel oil by about 46%. The used parameters values and assumptions are shown in Table 5.

Table 5. Parameters values and assumptions

C_p (Veziroğlu et al., 2008)	12.52 $\$/GJ$
Marine fuel heat content	42.7 MJ/kg
Marine fuel cost	0.41 $\$/kg$
Wind generation hydrogen cost (Bartels et al., 2010)	4.823 $\$/kg$

Conclusion

In order to comply with the more stringent environmental regulations, the design of green ships has received much attention in recent years. According to the last IMO study, CO_2 emissions may increase by 250 % by 2050 without using environmental regulations. Therefore, alternative propulsion systems and power sources need to be investigated that may be addressed using numerical simulation. Hybrid electric power systems have been suggested by the IMO to be adopted to reduce ship's fuel consumption and increase its efficiency. Using fuel cells as a source of power in hybrid systems increases its potential of reducing negative environmental impacts of shipping.

In this paper, we first present a three degree of freedom total ship system simulator that mathematically modelled in Simulink/MATLAB environment. This simulator has been validated using real ship operational data of a domestic ferry and simulation results show good agreement with the real data. For the same ferry, a hybrid fuel cell/battery propulsion system has been proposed and its performance has been simulated using the developed simulator. Results show that the proposed hybrid system has less weight and volume by 10% and 21% respectively compared to the conventional diesel propulsion system. However, the first cost of the hybrid fuel cell system is higher by 77% than the diesel engines but the commercialization of fuel cell and mass production will reduce its first cost and make it more cost competitive with conventional power sources. Moreover, hydrogen cost is higher than diesel oil by 46% for the examined voyage taking the environmental damage cost caused by fossil fuel into consideration.

Acknowledgement

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