Emission analysis of LNG fuelled molten carbonate fuel cell system for a chemical tanker ship: A case study

Omer Berkehan Inal1* • Cengiz Deniz1

1 Istanbul Technical University, Maritime Faculty, Marine Engineering Department, Tuzla/Istanbul, Turkey

ABSTRACT

Since sea transportation is one of the sources of air pollution and greenhouse gas emissions, so restrictive regulations are entering into force by the International Maritime Organisation to cope with the ship sourced emissions. Alternative energy generating systems are one of the key concepts and fuel cells can be one of the solutions for the future of the shipping industry by their fewer hazardous emissions compared to diesel engines. In this perspective, a Liquefied Natural Gas using molten carbonate fuel cell is evaluated instead of a conventional marine diesel engine for a chemical tanker ship. As a case study, the real navigation data for a tanker is gathered from the shipping company for the 27 voyages in 2018. Emissions are calculated respecting fuel types (marine diesel oil and heavy fuel oil) and designated Emission Control Areas for both diesel engine and fuel cell systems. The results show that more than 99% reduction in SOx, PM, and NOx emissions and a 33% reduction in CO2 emissions can be reached by the fuel cell system. At last, fuel cells seem very promising technologies especially for limited powered vessels under 5 MW for propulsion to use as main engines by complying with current and new coming emission limitations on the way of emission free shipping.

Please cite this paper as follows:

Inal, O. B., Deniz, C. (2021). Emission analysis of LNG fuelled molten carbonate fuel cell system for a chemical tanker ship: A case study. Marine Science and Technology Bulletin, 10(2): 118-133.

Introduction

Shipping transportation is more energy-efficient among different transportation modes (Alföldy et al., 2013; Zhu et al., 2018), and around 90% share of global trade is carried out by shipping transportation (Dere and Deniz, 2019; Harroud-Kolieb, 2008). Since 1990, more than a 150% increase occurred for the transportation of goods by sea and continuing to increase depending on the economic growth (Baldi et al., 2020). Despite its advantages in terms of cost, efficiency, operation ability, and reliability, shipping exhaust gases are substantially harmful emission sources for the environment. Besides the
In this regard, fuel cells are very promising and they can play a key role in their environmentally friendly power generation capacity (Inal and Deniz, 2018). Fuel cells can generate power without any air pollutants except CO2 even using carbon included fuel. Furthermore, they are highly modular and this is a very important factor specifically for limited space applications in transportation like submarines or commercial ships. Among the five commercial types of fuel cells; the proton exchange membrane fuel cells (PEMFC) are one of the most popular types (Sohani et al., 2020) with its high efficiency and technological maturity. However, the need for pure hydrogen as a fuel is very hard to handle for ships. Also, limited power output is a disadvantage for being the propulsion power generator for cargo ships (Inal and Deniz, 2020). For this reason, molten carbonate fuel cells (MCFC) and solid oxide fuel cells (SOFC) gain importance with their fuel flexibility and higher power capacity (van Bier, et al., 2016). Both are classified as high-temperature fuel cells and total system efficiency can be raised by heat recovery systems using high-quality exhaust gases (Wen et al., 2011; Martinić et al., 2018). The heat recovery capacity of the SOFC is higher than the MCFC thanks to its higher operating temperature which is approximately 200°C above (Buonomano et al., 2015). However, SOFC has some difficulties such as excessive thermal expansions due to its very high operating temperatures, less maturity than MCFC, and mechanical disadvantages (van Bier et al., 2016; Ahn et al., 2018). On the other hand, MCFC is demonstrated and commercially wider than SOFC, and on board ship applications were already practiced (McConnell, 2010; Tronstad et al., 2017). From this perspective, in the maritime industry, some fuel cell applications have been put into practice for on board electricity production instead of the diesel generators (De-Troya et al., 2016). For instance, in some of the projects; FellowSHIP project, a 330 kW MCFC is installed to offshore supply vessel "Viking Lady" and the system is demonstrated and commercially wider than SOFC, and on board ship applications were already practiced (McConnell, 2010; Tronstad et al., 2017). From this perspective, in the maritime industry, some fuel cell applications have been put into practice for on board electricity production instead of the diesel generators (De-Troya et al., 2016). For instance, in some of the projects; FellowSHIP project, a 330 kW MCFC is installed to offshore supply vessel "Viking Lady" and the system is demonstrated and commercially wider than SOFC, and on board ship applications were already practiced (McConnell, 2010; Tronstad et al., 2017). From this perspective, in the maritime industry, some fuel cell applications have been put into practice for on board electricity production instead of the diesel generators (De-Troya et al., 2016). For instance, in some of the projects; FellowSHIP project, a 330 kW MCFC is installed to offshore supply vessel "Viking Lady" and the system is demonstrated and commercially wider than SOFC, and on board ship applications were already practiced (McConnell, 2010; Tronstad et al., 2017). From this perspective, in the maritime industry, some fuel cell applications have been put into practice for on board electricity production instead of the diesel generators (De-Troya et al., 2016). For instance, in some of the projects; FellowSHIP project, a 330 kW MCFC is installed to offshore supply vessel "Viking Lady" and the system is demonstrated and commercially wider than SOFC, and on board ship applications were already practiced (McConnell, 2010; Tronstad et al., 2017).
fuel cell and marine diesel oil and fuel oil using diesel engines for a chemical tanker at the same power output. In this study, ten months of voyage data is collected from a shipping company of a chemical tanker ship in 2018. The tanker ship has a 4-stroke diesel engine with 2880 kW output power. Instead of the main engine, LNG using molten carbonate fuel cell with 2800 kW output would be installed for propelling. A new propulsion system is designed according to ship machinery room and out of use fuel tank conversion is discussed. The rest of this paper is organized as follows. In section 2, MCFC’s working principles and the designed system is described. In section 3, the case study is carried out by giving case ship and routes properties. In section 4, emissions of diesel and fuel cell versions are calculated and advantages and disadvantages were investigated. Finally, section 5 concludes the paper.

Molten Carbonate Fuel Cell (MCFC) and System Description

In this study, molten carbonate fuel cell is chosen to apply the tanker ship as a case study. The same generated propulsion power and being commercial type are the main motivation sources for selecting this fuel cell. Furthermore, fuel flexibility is another major effect of shipping. Also, the assessment of fuel cell types for commercial shipping was investigated in a previous study (Inal and Deniz, 2020).

Generally, in literature, fuel cells are categorized according to their working temperatures as low and high, and the molten carbonate fuel cell is one of the high temperature working fuel cells. Among high temperatures; MCFC works around 650°C and this high operation temperatures raise the total system efficiency (Marefati and Mehrpooya, 2019). The electrolyte is carbonates (Li_2CO_3 and K_2CO_3) and the electrodes in the MCFC are made of nickel materials (Mehmeti et al., 2016). As mentioned before, MCFC operating temperature is around 650°C and inside ion, conductivity occurs thanks to melted carbonate at 500°C (Ahn et al., 2018).

The proposed propulsion power generation system of the ship is illustrated in Figure 1. As seen in the figure, fuel is transferred to the mixer through a compressor and the mixture of natural gas and water is fed into the fuel cell stack. The delivered mixture pass to an internal reformer where water and natural gas react and produced hydrogen is given to the anode side of the fuel cell system. Before the internal reformer, reactants have to be heated to be prepared for an effective steam methane reforming (SMR) (2.1) and water gas shift reactions (WGS) (2.2) (Ahn et al., 2018) which are given below:

\[
\text{SMR: } \quad CH_4 + H_2O \leftrightarrow CO + 3H_2 \quad (2.1)
\]

\[
\text{WGS: } \quad CO + H_2O \leftrightarrow CO_2 + H_2 \quad (2.2)
\]

These two important reactions which occur to produce hydrogen and carbon monoxide inside of the fuel cell stack (Muñoz de Escalona et al., 2011). Since the reforming reaction is a deeply serious endothermic cycle, it ousts the heat delivered by the hydrogen oxidation (Kim and Lee, 2017). The electrochemical reactions in the MCFC are the followings (Mench, 2008; Ovrum and Dimopoulos, 2012):

Anode:

\[
H_2 + CO_3^{2-} \rightarrow CO_2 + H_2O + 2e^- \quad (2.3)
\]

\[
CO + CO_3^{2-} \rightarrow 2CO_2 + 2e^- \quad (2.4)
\]

Cathode:

\[
\frac{1}{2} O_2 + CO_2 + 2e^- \rightarrow CO_3^{2-} \quad (2.5)
\]

Overall:

\[
H_2 + \frac{1}{2} O_2 + CO_2 \rightarrow H_2O + CO_2 \quad (2.6)
\]

In this study, a commercial MCFC SureSource 3000 by Fuel Cell Energy Company is chosen for the case study. The fuel cell is comprised of two 1400 kW modules with total capacity of 2800 kW. The emission data of the fuel cell is collected from the manual of the product which is given in Table 1.

Table 1. Fuel cell specifications (Fuel Cell Energy, 2017)

| Specification          | SureSource 3000 MCFC |
|-----------------------|---------------------|
| Power Output          | 2800 kW             |
| Standard Frequency (Optional) | 60 Hz (50 Hz) |
| Exhaust Temperature   | 370 – 400 °C        |
| NOx Emission          | 0.0045 g/kWh        |
| SOx Emission          | 0.000045 g/kWh      |
| CO2 Emission          | 444.5 g/kWh         |
| PM Emission           | 9.07x10^-6 g/kWh    |
| Efficiency            | 47 +/- 2%           |
| Fuel Consumption (NG) | 615.12 m^3/h        |
| Sound Level           | 72 dB at 3m         |
| Maximum Height        | 6.6 m               |
| Cell Unit Length      | 6.5 m               |
| Cell Unit Width       | 13.1 m              |
In Figure 1, the proposed propulsion system for the case ship is represented. As seen in Figure 1, an air blower supplies the oxygen for the cathode reaction in the system. As well, the produced water by the fuel cell is gathered in a water tank to use again by the system for mixing with natural gas. After several electrochemical reactions in the fuel cell which are given above, the produced DC power is transformed into usable AC power by an inverter system which is included in the total fuel cell system under the title of the electrical balance of plant. The electrical power is converted to mechanical power after passing through the motor driver and electric motor. Then, the RPM of the electric motor is decreased to designed propeller RPM by a gearbox. At this point as being at the original version of the ship, a shaft generator can be used for the electrical need of the ship to use for navigation, HVAC, or accommodation space. Furthermore, the high-temperature exhaust gases can be used in a combined gas or steam turbine system as exhaust gas recovery to increase to total system efficiency. By the way, the ship is not equipped with a waste heat recovery system at the original version. Therefore, the system has not been analysed and is beyond the scope of this article.

**Case Study**

**Case Ship Description**

An oil/chemical tanker ship that has MAN STX 6L 32/40 with 2880 kW main engine power output is chosen as the case study reference ship for the molten carbonate fuel cell system. The case ship is equipped with a shaft generator, therefore during the courses, the electric need of the ship is provided by this system and diesel generators are in service during manoeuvring, emergencies, and when the vessel is berthed. Moreover, the ship is equipped with a controllable pitch propeller (CPP), the speed of the vessel is set by changing the angle of the blades of the propeller. Therefore, the main engine can work at fixed RPM to be more efficient.
The reference ship is using heavy fuel oil or marine diesel oil according to the sailing area. If the vessel enters to emission control area (ECA), fuel change over procedures entry into force due to emission limitations in 2018. Otherwise, because of the economic advantage, the company prefers to use fuel oil. In this paper, emissions are calculated for both marine diesel oil and fuel oil. The reference ship properties are listed in Table 2.

Table 2. Reference ship specifications

| Specifications          | Value             |
|------------------------|-------------------|
| Ship Type              | Oil / Chemical Tanker |
| Gross Tonnage          | 4829              |
| Deadweight             | 6970 tonnage      |
| Length                 | 119.1 m           |
| Breadth                | 16.9 m            |
| Year Built             | 2009              |
| Main Engine Power      | 2880 kW, 750 RPM  |
| Main Engine Sizes      | 10m × 5.5m × 2.5m |
| Shaft Generator        | 1500 kW           |
| Diesel Generator       | 3 set, 500 kW (each) |

The ship has different tanks such as the fuel oil (F/O), marine diesel oil (MDO), and lubricating oil (L/O) which can be transformed into LNG tanks. The tanks capacities according to ship plans are listed in Table 3. Other tanks will be needed during ship operations, such as; freshwater tanks, oily water tanks, bilge tanks, black and grey water tanks. After removing the main engine F/O, MDO and LO tanks won’t be needed anymore. To sum up, the total capacity of the tank, which can be switched to LNG tanks, is approximately 530 m³.

Table 3. Ship tank capacities

| Tank    | Volume (m³) |
|---------|-------------|
| F/O     | 421.64      |
| MDO     | 66.79       |
| L/O     | 41.57       |
| TOTAL   | 530 m³      |

After removing the main diesel engine some of the auxiliary equipment will be out of use. The list of the equipment with their approximate weights is given in Table 4. Some of the equipment names are given as a system due to their auxiliary equipment such as pumps, valves, and lines. This is why the approximate weights are increased.

Table 4. Out of use auxiliary equipment list

| Equipment                               | Quantity | Approx. Weight (kg) |
|-----------------------------------------|----------|---------------------|
| Fuel Oil Separator                      | 2 set    | 2 × 250             |
| Fuel Conditioning System                | 1 set    | 1 × 150             |
| Start Air Tubes                         | 2 set    | 3 × 100             |
| Start Air Compressors                   | 2 set    | 2 × 75              |
| Fresh Water Generator                   | 1 set    | 1 × 200             |
| Lubricating Oil Separator               | 1 set    | 1 × 250             |
| Sea Water Cooler System                  | 1 set    | 1 × 300             |
| Fresh Water Cooler System                | 1 set    | 1 × 400             |
| TOTAL                                   |          | 2250 kg             |

Route Description

The total ship voyage data in 2018 is collected from the company logs. According to collected data, the ship had 27 voyages generally in the Mediterranean Sea. The departure and arrival ports, distances (nautical mile), times spent at sea (hours) and average speeds (knots) of the vessel are given in Table 5. During its course for ten months, the case ship has sailed for approximately 3228 hours and 31469 nautical miles, generally in the Mediterranean Sea.

Several ports at the ship routes are in the Emission Control Areas (ECA) such as; Antwerp (Belgium) and Rotterdam (Netherlands). To enter to ECA zones, the ship must switch its fuel to low sulphur diesel oil from heavy fuel oil. This changeover causes to changes in emissions. Therefore, in this paper, to have more accurate calculations, a software program Netpas (Figure 4) is used to determine the correct distance by regarding the correct fuel type. Indeed, emission calculations are done by separating ECA.

For instance, in a case of total distance includes an ECA, the starting point of the area, and the destination port is calculated with low sulphur diesel oil besides the rest of the voyage is calculated with fuel oil.

Some of the distances between the same ports are different due to the change in the ship course as given in table 6. The average speed of the ship is calculated as 9.7 knots with a maximum speed of 10.91 and a minimum speed of 7.67 knots. The average speed variance graph is given at the Figure 5.
Figure 2. Bottom floor of the engine room

Figure 3. Second floor of the engine room
### Table 5. Reference ship routes

| No | Arrival       | Departure     | Distance (nm) | Time Spent at Sea (h) | Average Speed (kts) |
|----|---------------|---------------|---------------|-----------------------|---------------------|
| 1  | Ravenna       | Antwerp       | 3119.6        | 322                   | 9.69                |
| 2  | Koper         | Ravenna       | 136.5         | 13.83                 | 9.87                |
| 3  | Kulevi        | Koper         | 1815.85       | 176.17                | 10.31               |
| 4  | Constantza    | Kulevi        | 618.9         | 61.03                 | 10.14               |
| 5  | Elevisis      | Constantza    | 616.7         | 69.5                  | 8.87                |
| 6  | Ravenna       | Elevisis      | 953.7         | 87.42                 | 10.91               |
| 7  | Runcorn       | Ravenna       | 3085.9        | 302.58                | 10.20               |
| 8  | Aughinish     | Runcorn       | 576           | 57.33                 | 10.05               |
| 9  | Port Said     | Aughinish     | 3177.5        | 330                   | 9.63                |
| 10 | Haifa         | Port Said     | 223           | 25.25                 | 8.83                |
| 11 | Fos           | Haifa         | 1698.5        | 166                   | 10.23               |
| 12 | Aliaga        | Fos           | 1488.9        | 136.5                 | 10.91               |
| 13 | Gemlik        | Aliaga        | 324           | 31.05                 | 10.43               |
| 14 | Izmit Bay     | Gemlik        | 79            | 8                     | 9.88                |
| 15 | Augusta       | Izmit Bay     | 859.2         | 93.4                  | 9.20                |
| 16 | Berre         | Augusta       | 736.7         | 71.4                  | 10.32               |
| 17 | Augusta       | Berre         | 723           | 77.23                 | 9.36                |
| 18 | Izmit Bay     | Augusta       | 904.6         | 83.55                 | 10.83               |
| 19 | Aliaga        | Izmit Bay     | 306           | 35                    | 8.74                |
| 20 | Algeciras     | Aliaga        | 1673.3        | 159.4                 | 10.50               |
| 21 | Leixoes       | Algeciras     | 531.5         | 63.55                 | 8.36                |
| 22 | Safi          | Leixoes       | 851.5         | 111                   | 7.67                |
| 23 | Lavera        | Safi          | 1576.8        | 198                   | 7.96                |
| 24 | Livorno       | Lavera        | 299           | 29                    | 10.31               |
| 25 | Genoa         | Livorno       | 102           | 11.33                 | 9.00                |
| 26 | Haifa         | Genoa         | 1534.5        | 157                   | 9.77                |
| 27 | Rotterdam     | Haifa         | 3457          | 352                   | 9.82                |

### Table 6. Total ECA distance of case ship

| Voyage No | Departure | Arrival   | Total Distance (nm) | ECA Distance (nm) | ECA Time (h) |
|-----------|-----------|-----------|---------------------|-------------------|--------------|
| 1         | Ravenna   | Antwerp   | 3119.6              | 417               | 43           |
| 27        | Rotterdam | Haifa     | 3457                | 406               | 41.3         |
| TOTAL     |           |           | 6576.6              | 823               | 84.3         |
Also, the average speed of the ship changes regarding to ship load, sea and weather conditions. In addition, the average speed of the ship is accepted as the actual speed per each voyage for load ratio calculations in formula (4.1) where the actual and design power ratio is crucial for approximate emission calculations.

Results and Discussion

In this study, emissions are calculated according to main engine fuel consumption. Despite the specific fuel oil consumption (SFOC) and ship emissions depend on the engine load, generally, the total system load is smaller than the main
engine power capacity because usually ships sail between 60-80% engine load (Lee et al., 2020; Berstad, et al., 2013). Therefore, the specific fuel consumption is directly related to engine load. In this perspective, previously it should be calculated the load of the engine to find the SFOC. The ratio of the actual power \(P_{\text{actual}}\) and design power \(P_{\text{design}}\) is used to calculate the load ratio of the main engine. Also, load ratio \(L_R\) can be expressed as the ratio of actual speed \(v_{\text{actual}}\) and design speed \(v_{\text{design}}\) of the ship, prime the speed coefficient \(\alpha\) (Dere and Deniz, 2019; Moreno-Gutiérrez et al., 2015). The speed coefficient can vary between 2.5 and 3 (Moreno-Gutiérrez et al., 2015) and it is taken as 2.5 in this study. In addition, the design speed of the ship is 12 nautical miles and it is used for calculating the load ratio.

\[
L_R = \frac{P_{\text{actual}}}{P_{\text{design}}} = \left(\frac{v_{\text{actual}}}{v_{\text{design}}}\right)^\alpha \quad (4.1)
\]

Where \(P_{\text{actual}}\) becomes;

\[
P_{\text{actual}} = \left(\frac{v_{\text{actual}}}{v_{\text{design}}}\right)^\alpha \times P_{\text{design}} \quad (4.2)
\]

The SFOC actual can be calculated as following:

\[
SFOC_{\text{actual}} (g/kWh) = SFOC_{\text{base}} \times SFOC_{\text{ratio}} \quad (4.3)
\]

The SFOC\(_{\text{base}}\) is calculated according to the data at the manual of the main engine respecting each load per each voyage which is given in Table 5. On the other hand, the load ratio in formula (4.1) is used to calculate SFOC\(_{\text{ratio}}\), and the relationship between them is given as follows (Dere and Deniz, 2019; Moreno-Gutiérrez et al., 2015):

\[
SFOC_{\text{ratio}} (g/kWh) = 0.455L_R^2 - 0.71L_R + 1.28 \quad (4.4)
\]

Finally, the total estimated fuel consumption (EFC) according to main engine load of the ship is calculated in kilogram as following where the \(P_{\text{actual}}\) is calculated from the formula (4.2):

\[
EFC (kg) = P_{\text{actual}} (kW) \times SFOC_{\text{actual}} \left(\frac{\alpha}{200}\right) \times \text{Time (h)} \times 10^{-3} \quad (4.5)
\]

In case study fuel oil and diesel oil tanks would be transformed to LNG tanks. The total fuel oil tank capacity is 421 m\(^3\) and total diesel oil tank capacity is 66 m\(^3\) as mentioned in table 3. The maximum LNG consumption of the fuel cell for its longest route is 360 m\(^3\) for all voyages. The membrane type tank is selected for application in order to easier transformation and to be an already self-proving technology. The Moss type tank is another important alternative, however due to its spherical shape, during the transformation and adaptation of the system it would cause a severe volume loss inside the tanks. So, combined membrane system technology for LNG storage shows a great coherence during the transformation of the conventional oil tanks, related to its lower weight and membrane thickness. The volume reduction because of the insulation is calculated 96 m\(^3\) according to isolation layer of the combined system for the total of the both diesel oil and fuel oil tanks which is 487 m\(^3\), and this equals to 20% of volume loss from the total. Therefore, the maximum LNG transportation capacity reduces to 391 m\(^3\). The longest voyage of the chosen ship is determined and it is clearly seen that the new tank volume is satisfying for the vessel’s routes, so vessel wouldn’t need any LNG bunkering operation during its longest voyage.

Approximate total consumption of 1400 tons of marine diesel oil and heavy fuel oil are saved in 27 voyages via transformation, and according to 2020 ship bunker price, 95,000$ saving is expected when compared to LNG price. Furthermore, as a result of the system changing, lesser operational and periodic maintenance expenditure and so labour force add more financial gain and diminish the risk due to human factor in the system as well. The major equipment for maintenance is the mechanical equipment of plant and its components. These types of auxiliary maintenance are almost same with the conventional diesel engines and their equipment such as pumps, compressors, valves and filters, so neither disadvantages nor advantages cannot be designated. The major fuel cell maintenance need occurs at the end of its lifecycle by changing of the electrolyte and electrodes. However, the lifetime and carbon footprint of the fuel cells should be investigated and therefore the difference with diesel engines and costs for the renewing the electrolyte should be identified.

**CO\(_2\) Emissions**

The emissions of main diesel engines have been calculated according to estimated fuel consumption. The case ship can use both fuel oil and marine diesel oil in diesel engine, so CO\(_2\) emissions are calculated according to fuel type including LNG for fuel cell, as seen in Figure 6. The fuel changeover has been taken into account regarding ship routes in ECA and emissions are calculated respecting fuel types.

The CO\(_2\) emission coefficients are taken 3.206 and 3.114 for marine diesel oil and heavy fuel oil, respectively (MEPC, 2018). The table according to conversion factor between fuel consumption and CO\(_2\) emission is shown at Table 7. On the other hand, for both LNG fuel cell system, it is calculated by using manual data at given in Table 1.
The calculations are done according to following formulas:

\[
CO_2 \text{ Emission (kg) for MCFC} = 444.5 \left( \frac{g}{\text{kWh}} \right) \times \text{Pactual (kW)} \times \text{Time (h)} \times 10^{-3} \tag{4.6}
\]

\[
CO_2 \text{ Emission (kg) for MDO Diesel Engine} = 3.206 \times \text{EFC (kg)} \tag{4.7}
\]

\[
CO_2 \text{ Emission (kg) for HFO Diesel Engine} = 3.114 \times \text{EFC (kg)} \tag{4.8}
\]

Table 7. Conversion factor between fuel consumption and CO2 emission (MEPC, 2018)

| Fuel Type                  | Reference                              | Carbon Content | Conversion Factor |
|----------------------------|----------------------------------------|----------------|------------------|
| Diesel / Gas Oil           | ISO 8217 Grades DMX through DMB        | 0.8744         | 3.206            |
| Light Fuel Oil (LFO)       | ISO 8217 Grades RMA through RMD        | 0.8594         | 3.151            |
| Heavy Fuel Oil (HFO)       | ISO 8217 Grades RME through RMK        | 0.8493         | 3.114            |
| Liquefied Natural Gas (LNG)| -                                      | 0.75           | 2.750            |

Table 7. Conversion factor between fuel consumption and CO2 emission (MEPC, 2018)

Figure 6. CO2 emissions according to the fuel type and voyage number

The results show that more than 1200 tons of CO2 emissions decrease approximately 33% with the LNG fuel cell system for the same power output during the same route and sailing hours compared to the diesel engine. The case ship is already equipped with a shaft generator. Therefore, the diesel generators are not in use for energy needs of the ship during sailing. However, during tank washing, as a classical need for a chemical tanker, the total electrical need is maximizing. Since the selected fuel cell type has a high temperature exhaust, gas a waste heat recovery system can be applied. As a result, this additional power need can be supplied by a waste heat recovery system by increasing the total system efficiency and also by decreasing greenhouse gas emission.

As a result of the proposed system, the new EEDI is calculated according to new CO2 emissions to see the ship is in compliance with the requirements. The calculation has several steps to reach the attained EEDI so firstly, baseline (4.9) and required EEDI (4.10) must be found for benchmarking.

\[
\text{Baseline} = a \times b^{-c} \tag{4.9}
\]

In equation (4.9), \(a\) is 1218.80, \(b\) is deadweight of the ship and lastly, \(c\) is 0.488 for a tanker ship (IMO, 2015).

\[
\text{Required EEDI} = \left(1 - \frac{x}{100}\right) \times \text{Baseline} \tag{4.10}
\]

In equation (4.10), \(x\) is defined as reduction factor and varies according to ship’s deadweight and EEDI phase. In this paper, phase 1 (01 January 2015 – 31 December 2019) and phase 2 (01 January 2020 – 31 December 2024) are taken into account for calculations because of the case ship’s voyage period which was during phase 1 but new reduction factor during preparations of this paper which is in phase 2.
the maximum allowable NO\textsubscript{x} emission can be found 9.59 g/kWh. Therefore, NO\textsubscript{x} emission per voyage can be found using the following equations (4.13) and (4.14):

The results of emissions are shown in Figure 7 where the fuel cell emissions are at the left column and the diesel engine emissions are at the right according to ship voyage.

As a result, more than 99% emission, more than 53 tons of NO\textsubscript{x} decrease is calculated, totally. As expected, the main reason for NO\textsubscript{x} formation in diesel engines is the air for internal combustion. However, in fuel cell systems, the electrical power is produced directly by converting the chemical energy of the fuel. So, the differentiating factor and the source of nitrogen at this point is the need for air for conventional engines. In other words, fuel cell NO\textsubscript{x} emission is negligible compared to diesel engines and this shows great potential for the future of shipping and in the meaning of strict emission regulations.

**SO\textsubscript{x} Emissions**

In the maritime industry, the dominant fuel types are sulphur blended fuels such as marine diesel oil and heavy fuel oil which is the main reason for SO\textsubscript{x} formation by marine diesel engines. In this paper, the reference ship routes are collected for the year 2018. However, at the beginning of 2020 outside ECA SO\textsubscript{x} emission limit is decreased to 0.5% from 3.5%. On the other hand, inside ECA sulphur content in fuel was reduced to 0.1% for ECA and 3.5% and 0.5% for outside ECA, for the years 2018 and 2020, respectively, were accepted in the calculations summarized in table 6. Thus, fuel with a sulphur content of 0.1% for ECA and 3.5% and 0.5% for outside ECA, for the years 2018 and 2020, respectively, were accepted in the calculations according to ISO 8217. SO\textsubscript{x} emissions are calculated according to formulas (4.15) and (4.16) where, 0.97553 is the fraction of fuel sulphur converted to SO\textsubscript{x} and 2 is the ratio of molecular weight of SO\textsubscript{x} and sulphur (IMO, 2015):

\[
\text{SO}\textsubscript{x} (\text{kWh}) = \text{SFOC}\textsubscript{actual} \cdot \left( \frac{\text{g}}{\text{kWh}} \right) \times 2 \times 0.97753 \times \%\text{fuel sulphur fraction} \tag{4.15}
\]

\[
\text{SO}\textsubscript{x} (\text{kg}) = \text{SO}\textsubscript{x} \left( \frac{\text{g}}{\text{kWh}} \right) \times \text{P}\text{actual} \times \text{Time} \times 10^{-3} \tag{4.16}
\]

**NO\textsubscript{x} Emissions**

The case ship has an engine that satisfies IMO Tier II NO\textsubscript{x} emission limits. Since 2011, the Tier II global emission limitation depends on the engine speed, and for the engines working between 130 and 2000 rpm can be calculated with (4.12) where the \( n \) is the engine speed (IMO, 2016).

Therefore, since the main engine maximum operating speed is 750 rpm for our case ship, according to the formula (4.12),

\[
\text{The maximum allowable NO}\textsubscript{x} emission (kg) = 44 \times n^{-0.23} \tag{4.12}
\]

\[
\text{NO}\textsubscript{x} emission for diesel (kg) = 9.59 \left( \frac{\text{g}}{\text{kWh}} \right) \times P_{\text{actual}} (\text{kW}) \times \text{Time} (\text{h}) \times 10^{-3} \tag{4.13}
\]

\[
\text{NO}\textsubscript{x} emission for MCFC (kg) = 0.0045 \left( \frac{\text{g}}{\text{kWh}} \right) \times P_{\text{actual}} (\text{kW}) \times \text{Time} (\text{h}) \times 10^{-3} \tag{4.14}
\]

The results of emissions are shown in Figure 7 where the fuel cell emissions are at the left column and the diesel engine emissions are at the right according to ship voyage.

As a result, more than 99% emission, more than 53 tons of NO\textsubscript{x} decrease is calculated, totally. As expected, the main reason for NO\textsubscript{x} formation in diesel engines is the air for internal combustion. However, in fuel cell systems, the electrical power is produced directly by converting the chemical energy of the fuel. So, the differentiating factor and the source of nitrogen at this point is the need for air for conventional engines. In other words, fuel cell NO\textsubscript{x} emission is negligible compared to diesel engines and this shows great potential for the future of shipping and in the meaning of strict emission regulations.

| Table 8. Parameters used in equation (4.11) |
|------------------------------------------------|
| Parameter | Explanation |
| P\text{ME} | Main engine power |
| C\text{FME} | Carbon content of fuel used in main engine |
| SFC\text{ME} | Specific fuel consumption of main engine |
| P\text{AE} | Auxiliary engine power |
| C\text{FAE} | Carbon content of fuel used in auxiliary engine |
| SFC\text{AE} | Specific fuel consumption of auxiliary engine |
| P\text{PTI} | Power consumption of shaft motor |
| P\text{Aeff} | Power of innovative technology |
| P\text{eff} | Efficiency of the innovative technology |
| Capacity | Deadweight tonnage of the ship |
| V\text{ref} | Ship speed |
| f\text{c} | Correction factor to account for ship specific design elements |
| f\text{itt} | Availability factor of innovative energy efficiency technology |
| f\text{c} | Capacity factor for any technical limitation on capacity |
| f\text{c} | Cubic capacity correction factor |
| f\text{w} | Coefficient indicating the decrease of speed caused by sea condition |

| Table 9. EEDI results |
|-----------------------|
| Baseline | 16.23 |
| Required EEDI phase 1 | 15.92 |
| Required EEDI phase 2 | 15.62 |
| Diesel Engine EEDI | 15.34 |
| Fuel Cell EEDI | 10.38 |
In Figure 8, SO\textsubscript{x} emissions are shown with two different emission regulations for diesel engines for each voyage. The emission results for diesel engine in 2020 are according to today’s rules. Since the case ship navigated in ECA, total sum of diesel oil and fuel oil is calculated for voyage number 1 and 27. The total emissions for 27 voyages in 2018 are calculated and more than 99% and 98% emission reduction can be reached against 2018 and today’s fuel types. Regarding to 2020 emission regulations, more than 11 tons of SO\textsubscript{x} emission reduction is reached with fuel cell systems. Since the natural gas is a sulphur free fuel, it is a good option with the aim of staying under limits for the maritime industry also with dual-fuel marine engines.

**Particulate Matter (PM) Emissions**

Particulate matter is one of the polluting emissions from ships. PM emissions are directly dependent on the sulphur content of the consumed fuel like SO\textsubscript{x}. In the case of reducing sulphur blended fuel usage, PM emissions are also showing a decreasing trend. According to MARPOL Annex VI emission regulations, PM emissions are one of the major topics. PM emission for the diesel engine is calculated using formula (4.17) where SF is the sulphur fraction of the fuel (IMO, 2015):
\[ PM(kg) = \left[ 1.35 + SFOC \times 7 \times 0.02247 \times (SF - 0.0246) \right] \times P_{\text{actual}} \times \text{Time (h)} \times 10^{-3} \]  

(4.17)

The total PM emission for the diesel engine is 9506 kg for all 27 voyages. However, fuel cell’s PM emissions are negligible and almost totally eliminated compared to diesel engines. Therefore, it is not shown in Figure 9.

**Conclusion**

There are numerous methods to reduce the ship sourced emissions in shipping industry; however, their high operational and installation costs and diminishing of fossil fuel reserve are forcing ship owners to invest in new environmental friendly power sources. Due to strict international regulations on GHG and air polluting emissions in shipping, as a major exhaust gas producers, main engines of vessels must be switched from diesel engines to zero emission power producing technologies. At this point hydrogen fuel cells are important alternatives with their water emissions but high cost of hydrogen production and difficulties on storage of hydrogen make their usage difficult in shipping. Therefore, another fuel cell type, molten carbonate, a high temperature working fuel cell, is investigated in this research thanks by considering to its capability of using LNG as a fuel.

In this paper, a chemical tanker was dealt with case study using real routes in 2018 that were received from the company logs. LNG fuelled MCFC, which has same power output with ship’s main diesel engine, is studied for the ship main propulsion system. The case routes are investigated respecting ECA using Netpas software and fuel switching procedures. The fuel type of the main engine is taken into account while calculating the emissions. Approximately, more than 99% of SOx, PM, and NOx and 33% of CO2 emission reductions are calculated. Furthermore, 11402 kg of SOx, 9506 kg of PM, 53668 kg NOx and 1223 tons of CO2 emissions is reduced just by one ship for 27 voyages in the Mediterranean Sea. The reduction at SOx was expected due to LNG characteristics but in contrast, the reduction at CO2 emissions is important in comparison to LNG fuelled diesel engines. However, the lifetime and carbon footprint of the fuel cells should be investigated and therefore the difference with diesel engines and costs for the renewing the electrolyte should be identified.

The new system is designed with respect to auxiliary system components like compressors or additional pumps. Hence, previous equipment such as fuel separators, fresh water generator, lubricating oil tanks and related pumps and heat exchangers will be out of use. The transformation of the fuel tanks to LNG may be another challenge for the new system, at least LNG use in shipping is a mature technology than hydrogen usage and there is enough experience to handle it. The electrical components are very reliable systems for years, so, their failure and maintenance need is neglected. In addition, suitability for co-generation systems for the MCFC by waste heat recovery system was another motivating reason for ship case study. However, in the original version, case ship is not equipped by a waste heat system. So, comparison with cogeneration system would not be useful to see the results clearly.
For further studies, similar cases can be investigated for different ship types and different routes under economical perspective with considering supply chain and bunkering operations of hydrogen or LNG. Moreover, noise and vibration effects and response for instantaneous load changes of the system can be investigated for the fuel cell powered ships. Operational procedures, system risk assessments and maintenance cost and frequency can also be an interesting area to study.

Compliance with Ethical Standards

Conflict of Interest

The authors declare that they have no competing interests.

Ethical Approval

For this type of study, formal consent is not required.

Availability of Data and Materials

The data that support the findings of this study are available from Chemfleet Ship Management but restrictions apply to the availability of these data, which were used under license for the current study, and so are not publicly available. Data are however available from the authors upon reasonable request and with permission of Chemfleet Ship Management.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

References

Ahn, J., Park, S. H., Lee, S., Noh, Y. & Chang, D. (2018). Molten carbonate fuel cell (MCFC)-based hybrid propulsion systems for a liquefied hydrogen tanker. *International Journal of Hydrogen Energy*, 43(15): 7525–7537. https://doi.org/10.1016/j.ijhydene.2018.03.015

Allöldy, B., Lööv, J. B., Lagler, F., Mellqvist, J., Berg, N., Beecken, J., Weststrate, H., Duyzer, J., Bencs, L., Horemans, B., Cavalli, F., Putaud, J.-P., Janssens-Maenhout, G., Csordás, A. P., Van Grieken, R., Borowiak, A. & Hjorth, J. (2013). Measurements of air pollution emission factors for marine transportation in SECA. *Atmospheric Measurement Techniques*, 6(7): 1777-1791. https://doi.org/10.5194/amt-6-1777-2013

Ammar, N. R. & Seddiek, I. S. (2020). An environmental and economic analysis of emission reduction strategies for container ships with emphasis on the improved energy efficiency indexes. *Environmental Science and Pollution Research*, 27(18): 23342–23355. https://doi.org/10.1007/s11356-020-08861-7

Baldi, F., Moret, S., Tammi, K. & Maréchal, F. (2020). The role of solid oxide fuel cells in future ship energy systems. *Energy*, 194: 116811. https://doi.org/10.1016/j.energy.2019.116811

Bennabi, N., Charpentier, J. F., Menana, H., Billard, J. Y. & Genet, P. (2016). Hybrid propulsion systems for small ships: Context and challenges. In Proceedings - 2016 22nd International Conference on Electrical Machines, ICEM 2016 (pp. 2948–2954). https://doi.org/10.1109/ICELMACH.2016.7732943

Berstad, D., Anantharaman, R. & Nekså, P. (2013). Low-temperature CO2 capture technologies – Applications and potential. *International Journal of Refrigeration*, 36(5): 1403–1416. https://doi.org/10.1016/j.ijrefrig.2013.03.017

Brynof, S., Magnusson, M., Fridell, E. & Andersson, K. (2014). Compliance possibilities for the future ECA regulations through the use of abatement technologies or change of fuels. *Transportation Research Part D: Transport and Environment*, 28(X): 6–18. https://doi.org/10.1016/j.trd.2013.12.001

Buonomano, A., Calise, F., d’Accadia, M. D., Palombo, A., & Vicedomini, M. (2015). Hybrid solid oxide fuel cells–gas turbine systems for combined heat and power: A review. *Applied Energy*, 156: 32–85. https://doi.org/10.1016/j.apenergy.2015.06.027

Deniz, C. & Zincir, B. (2016). Environmental and economical assessment of alternative marine fuels. *Journal of Cleaner Production*, 113: 438–449. https://doi.org/10.1016/j.jclepro.2015.11.089

Dere, C. & Deniz, C. (2019). Load optimization of central cooling system pumps of a container ship for the slow steaming conditions to enhance the energy efficiency. *Journal of Cleaner Production*, 222: 206–217. https://doi.org/10.1016/j.jclepro.2019.03.030

Dere, C. & Deniz, C. (2020). Effect analysis on energy efficiency enhancement of controlled cylinder liner temperatures in marine diesel engines with model based approach. *Energy Conversion and Management*, 220: 113015. https://doi.org/10.1016/j.enconman.2020.113015
De-Troya, J. J., Álvarez, C., Fernández-Garrido, C. & Carral, L. (2016). Analysing the possibilities of using fuel cells in ships. *International Journal of Hydrogen Energy, 41*(4): 2853–2866. https://doi.org/10.1016/j.ijhydene.2015.11.145

Díaz-de-Baldasano, M. C., Mateos, F. J., Núñez-Rivas, L. R. & Leo, T. J. (2014). Conceptual design of offshore platform supply vessel based on hybrid diesel generator-fuel cell power plant. *Applied Energy, 116*: 91–100. https://doi.org/10.1016/j.apenergy.2013.11.049

Fuel Cell Energy. (2017). SureSource 3000 Datasheet. URL https://www.fuelcellenergy.com/wp-content/uploads/2017/02/Product-Spec-SureSource-3000.pdf (accessed 21.08.20)

Ghenai, C., Bettayeb, M., Brdjanin, B. & Hamid, A. K. (2019). Hybrid solar PV/PEM fuel Cell/Diesel Generator power system for cruise ship: A case study in Stockholm, Sweden. *Case Studies in Thermal Engineering, 14*: 100497. https://doi.org/10.1016/j.csite.2019.100497

Hansson, J., Månsson, S., Brynolf, S. & Grahn, M. (2019). Alternative marine fuels: Prospects based on multi-criteria decision analysis involving Swedish stakeholders. *Biomass and Bioenergy, 126*: 159–173. https://doi.org/10.1016/j.biombioe.2019.05.008

Harrould-Kolieb, E. (2008). *Shipping Impacts on Climate: A Source with Solution*. Oceana: Washington, USA.

IMO. (2011). Marine Environment Protection Committee (MEPC), 62nd session. URL http://www.imo.org/en/OurWork/Environment/PollutionPrevention/AirPollution/Pages/Technical-and-Operational-Measures.aspx (accessed 11.10.20)

IMO. (2015). *Third IMO Greenhouse Gas Study 2014*. International Maritime Organization (IMO). London: International Maritime Organization. https://doi.org/10.1007/s10584-013-0912-3

IMO. (2016). Nitrogen Oxides (NOx) - Regulation 13. URL http://www.imo.org/en/OurWork/Environment/PollutionPrevention/AirPollution/Pages/Nitrogen-oxides-(NOx)-%E2%80%93-Regulation-13.aspx (accessed 11.10.20)

IMO. (2018). Marine Environment Protection Committee (MEPC), 72nd session. URL http://www.imo.org/en/MediaCentre/MeetingSummaries/MEPC/Pages/MEPC-72nd-session.aspx (accessed 11.10.20).

Inal, O. B. & Deniz, C. (2018). Fuel cell availability for merchant ships. In *Proceedings of the 3rd International Naval Architecture and Maritime Symposium* (pp. 907–916). Istanbul, Turkey.

Inal, O. B. & Deniz, C. (2020). Assessment of fuel cell types for ships: Based on multi-criteria decision analysis. *Journal of Cleaner Production, 265*: 121734. https://doi.org/10.1016/j.jclepro.2020.121734

Inal, O.B. (2018). Analysis of the availability and applicability of fuel cell as a main power unit for a commercial ship. MSc Thesis. Istanbul Technical University, Istanbul, Turkey.

Karaat, Ş. & Durmuşoğlu, Y. (2020). Design of a solar photovoltaic system for a Ro-Ro ship and estimation of performance analysis: A case study. *Solar Energy, 207*: 1259–1268. https://doi.org/10.1016/j.solener.2020.07.037

Kim, Y. J. & Lee, M. C. (2017). Comparison of thermal performances of external and internal reforming molten carbonate fuel cells using numerical analyses. *International Journal of Hydrogen Energy, 42*(5): 3510–3520. https://doi.org/10.1016/j.ijhydene.2016.10.165

Lee, H., Jung, I., Roh, G., Na, Y. & Kang, H. (2020). Comparative analysis of on-board methane and methanol reforming systems combined with HT-PEM fuel cell and CO2 capture/liquefaction system for hydrogen fueled ship application. *Energies, 13*(1): 224. https://doi.org/10.3390/en13010224

Marefati, M. & Mehrpooya, M. (2019). Introducing and investigation of a combined molten carbonate fuel cell, thermoelectric generator, linear fresnel solar reflector and power turbine combined heating and power process. *Journal of Cleaner Production, 240*: 118247. https://doi.org/10.1016/j.jclepro.2019.118247

Martinić, F., Radica, G. & Barbir, F. (2018). Application and analysis of solid oxide fuel cells in ship energy systems. *Brodogradnja*, 69(4): 53–68. https://doi.org/10.21278/brod69405

McConnell, V. P. (2010). Now, voyager? The increasing marine use of fuel cells. *Fuel Cells Bulletin, 2010*(5): 12–17. https://doi.org/10.1016/S1464-2859(10)70166-8

Mehmeti, A., Santoni, F., Della Pietra, M. & McPhail, S. J. (2016). Life cycle assessment of molten carbonate fuel cells: State of the art and strategies for the future. *Journal of Power Sources, 308*: 97–108. https://doi.org/10.1016/j.jpowsour.2015.12.023

Mench, M. M. (2008). *Fuel Cell Engines*. WILEY. John Wiley & Sons, Inc. https://doi.org/10.1002/9780470209769
MEPC. (2018). Resolution MEPC.308(73), Guidelines on the Method of Calculation of the Attained Energy Efficiency Design Index (EEDI) for New Ships.

Moreno-Gutiérrez, J., Calderay, F., Saborido, N., Boile, M., Rodríguez Valero, R. & Durán-Grados, V. (2015). Methodologies for estimating shipping emissions and energy consumption: A comparative analysis of current methods. *Energy*, 86: 603–616. https://doi.org/10.1016/j.energy.2015.04.083

Muñoz de Escalona, J. M., Sánchez, D., Chacartegui, R. & Sánchez, T. (2011). A step-by-step methodology to construct a model of performance of molten carbonate fuel cells with internal reforming. *International Journal of Hydrogen Energy*, 36(24): 15739–15751. https://doi.org/10.1016/j.ijhydene.2011.08.094

Ovrum, E. & Dimopoulos, G. (2012). A validated dynamic model of the first marine molten carbonate fuel cell. *Applied Thermal Engineering*, 35: 15–28. https://doi.org/10.1016/j.applthermaleng.2011.09.023

Psaraftis, H. N. & Kontovas, C. A. (2014). Ship speed optimization: Concepts, models and combined speed-routing scenarios. *Transportation Research Part C: Emerging Technologies*, 44: 52–69. https://doi.org/10.1016/j.trc.2014.03.001

Raptotasis, S. I., Sakellaridis, N. F., Papagiannakis, R. G. & Hountalas, D. T. (2015). Application of a multi-zone combustion model to investigate the NOx reduction potential of two-stroke marine diesel engines using EGR. *Applied Energy*, 157: 814–823. https://doi.org/10.1016/j.apenergy.2014.12.041

Sohani, A., Naderi, S., Torabi, F., Sayyaadi, H., Golizadeh Akhlaghi, Y., Zhao, X., Talukdar, K. & Said, Z. (2020). Application based multi-objective performance optimization of a proton exchange membrane fuel cell. *Journal of Cleaner Production*, 252: 119567. https://doi.org/10.1016/j.jclepro.2019.119567

Strazza, C., Del Borghi, A., Costamagna, P., Traverso, A. & Santin, M. (2010). Comparative LCA of methanol-fuelled SOFCs as auxiliary power systems on-board ships. *Applied Energy*, 87(5): 1670–1678. https://doi.org/10.1016/j.apenergy.2009.10.012

Tronstad, T., Åstrand, H. H., Haugom, G. P. & Langfeldt, L. (2017). Study on the use of Fuel Cells in Shipping. DNV GL – Maritime: Hamburg, Germany. 106p.

Tse, L. K. C., Wilkins, S., McGlashan, N., Urban, B. & Martínez-Botas, R. (2011). Solid oxide fuel cell/gas turbine trigeneration system for marine applications. *Journal of Power Sources*, 196(6): 3149–3162. https://doi.org/10.1016/j.jpowsour.2010.11.099

Uyanık, T., Karatuğ, Ç. & Arslanoğlu, Y. (2020). Machine learning approach to ship fuel consumption: A case of container vessel. *Transportation Research Part D: Transport and Environment*, 84: 102389. https://doi.org/10.1016/j.trd.2020.102389

van Biert, L., Godjevac, M., Visser, K. & Aravind, P. V. (2016). A review of fuel cell systems for maritime applications. *Journal of Power Sources*, 327: 345–364. https://doi.org/10.1016/j.jpowsour.2016.07.007

Wee, J.-H. (2011). Molten carbonate fuel cell and gas turbine hybrid systems as distributed energy resources. *Applied Energy*, 88(12): 4252–4263. https://doi.org/10.1016/j.apenergy.2011.05.043

Zhu, M., Yuen, K. F., Ge, J. W. & Li, K. X. (2018). Impact of maritime emissions trading system on fleet deployment and mitigation of CO₂ emission. *Transportation Research Part D: Transport and Environment*, 62: 474–488. https://doi.org/10.1016/j.trd.2018.03.016

Zincir, B. A. (2020). Comparison of the carbon capture systems for on board application and voyage performance investigation by a case study. MSc. Thesis. Istanbul Technical University.