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RESEARCH ARTICLE

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

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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 SO_x, PM, and NO_x emissions and a 33% reduction in CO_2 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.

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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; Harrould-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

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major pollutants; nitrogen oxides (NO_x), sulphur oxides (SO_x), particulate matter (PM), carbon dioxide (CO_2), and volatile organic compounds (VOCs) emissions are also taking an important place for the maritime industry (Ammar and Seddiek, 2020). According to the Third Greenhouse Gas Study which is carried out by the International Maritime Organization (IMO), for the year 2012, the total and international shipping CO_2 emissions were estimated to approximately 938 and 796 million tons which contribute 3.1% and 2.6% of global CO_2 emissions, respectively (IMO, 2015). In 2018, by aiming to minimize the total amount of greenhouse gases with environmental negative impacts by at least 50% by 2050 compared to levels in 2008, IMO put into force more stringent regulations (IMO, 2018). From this perspective, IMO has introduced the Energy Efficiency Design Index (EEDI), the Ship Energy Efficiency Management Plan (SEEMP), and Energy Efficiency Operational Indicator (EEOI) in MARPOL Annex VI in 2013 (IMO, 2011). To achieve emission reduction from ships, and to stay under limitations, various options must be well analysed and introduced such as increasing engine efficiency with a more efficient energy management plan (Uyanık et al., 2020), load, road, and speed optimization (Psaraftis and Kontovas, 2014), slow steaming (Dere and Deniz, 2020), alternative marine fuels (Deniz and Zincir, 2016; Hansson et al., 2019), auxiliary solar PV systems (Karatuğ and Durmuşoğlu, 2020), hybrid and electric propulsion systems (Bennabi et al., 2016) or exhaust gas cleaning systems (Lee et al., 2020; Zhu et al., 2018). However, according to exhaust gas contents, treatment technology varies, and therewithal to reduce NO_x emission, there are Exhaust Gas Recirculation (EGR) and Selective Catalytic Reduction after treatment (SCR) (Raptotasios et al., 2015). Besides, scrubbers play a key role to reduce SO_x emission from power generation and propulsion on board (Brynolf et al., 2014).

On the other hand, possible changes in ship designs such as modification of hull form or propelling systems, are also taking interest of researchers, however still do not address the final solution of this emission problem (Baldi et al., 2020). Another important option for shipping is Diesel-electric propulsion systems which help to reduce emissions by fuel-saving because engines can operate with high efficiency at high and constant load, however maritime stakeholders still need to comply with the environmental regulations (Ghenai et al., 2019) The battery-powered ships also seem another option for the future of shipping mostly used in hybrid systems with expected savings up to 20% but there are only infrequent cases and because of the limited battery capacity and high cost, it is not feasible for long-range intercontinental shipping (Moe, 2016).

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 CO_2 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 Biert, 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 (Wee, 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 Biert 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 operated for 18 hours (Tronstad et al., 2017); METHAPU project, methanol fed 20 kW SOFC is applied to a RoRo ship (Strazza et al., 2010); FELICITAS project, a 250 kW SOFC is tested in a mega yacht (Tse et al., 2011); SchIBZ project, a 500 kW diesel internal reforming SOFC powered the propulsion (van Biert et al., 2016), and methanol fed 500 kW MCFC is installed into an offshore vessel by hybridization with diesel engine (Díaz-de-Baldasano et al., 2014). The fuel cells seem promising for the future of the shipping industry by their fewer hazardous emissions and depending on the technological developments they can be replaced marine diesel engines not only electric generation but also propelling.

The purpose of this paper is to investigate the emission variance between a commercial LNG fuelled molten carbonate 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:

SMR: $$CH_4 + H_2O \leftrightarrow CO + 3H_2 \quad (2.1)$$

WGS: $$CO + H_2O \leftrightarrow CO_2 + H_2 \quad (2.2)$$

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
NO_x Emission	0.0045 g/kWh
SO_x Emission	0.000045 g/kWh
CO_2 Emission	444.5 g/kWh
PM Emission	9.07×10^{-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

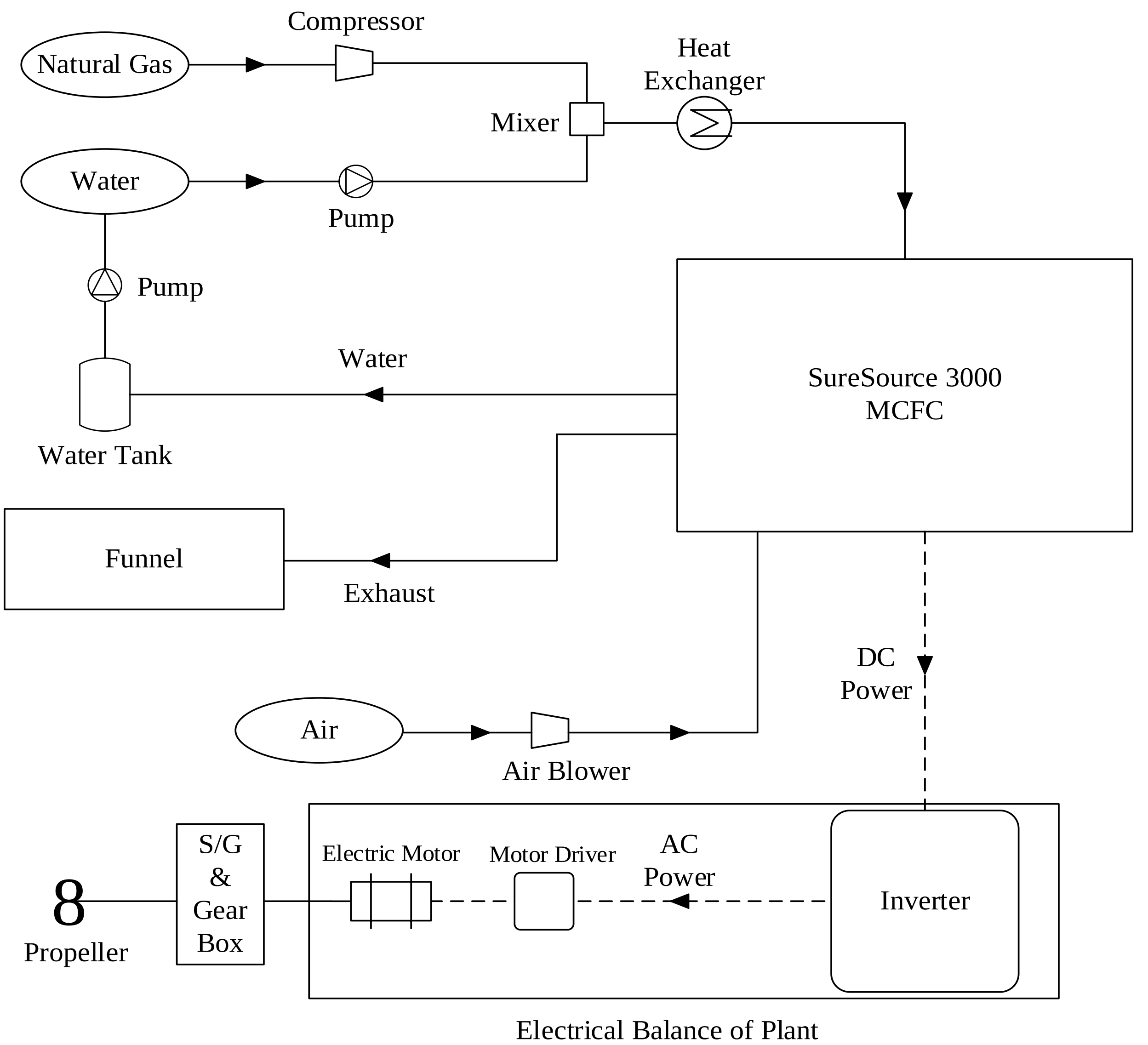

Figure 1. Schematic representation of the propulsion system

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	
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 m^3.

Table 3. Ship tank capacities

Tank	**Volume (m^3)**
F/O	421.64
MDO	66.79
L/O	41.57
TOTAL	530 m^3

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.

The vessel engine room consists of 3 floors. The main engine, shaft, several tanks, and pumps are located at the bottom floor, the plan is in Figure 2. Three diesel generators, fuel oil, diesel oil and lubricating oil separators (located in separator room), air compressors and start air tanks, freshwater generator system, some other tanks, and steering room are located in the second floor, as seen in Figure 3. The third floor consists engine control room, workshop, incinerator room, and boiler room, therefore any kind of displacement due to the fuel cell system will not occur on this floor. Also, some of the tanks like freshwater or fuel oil are longitudinal, so, they have parts on both floors. The total engine room volume is fairly enough for the proposed modular fuel cell system and its auxiliary units.

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.

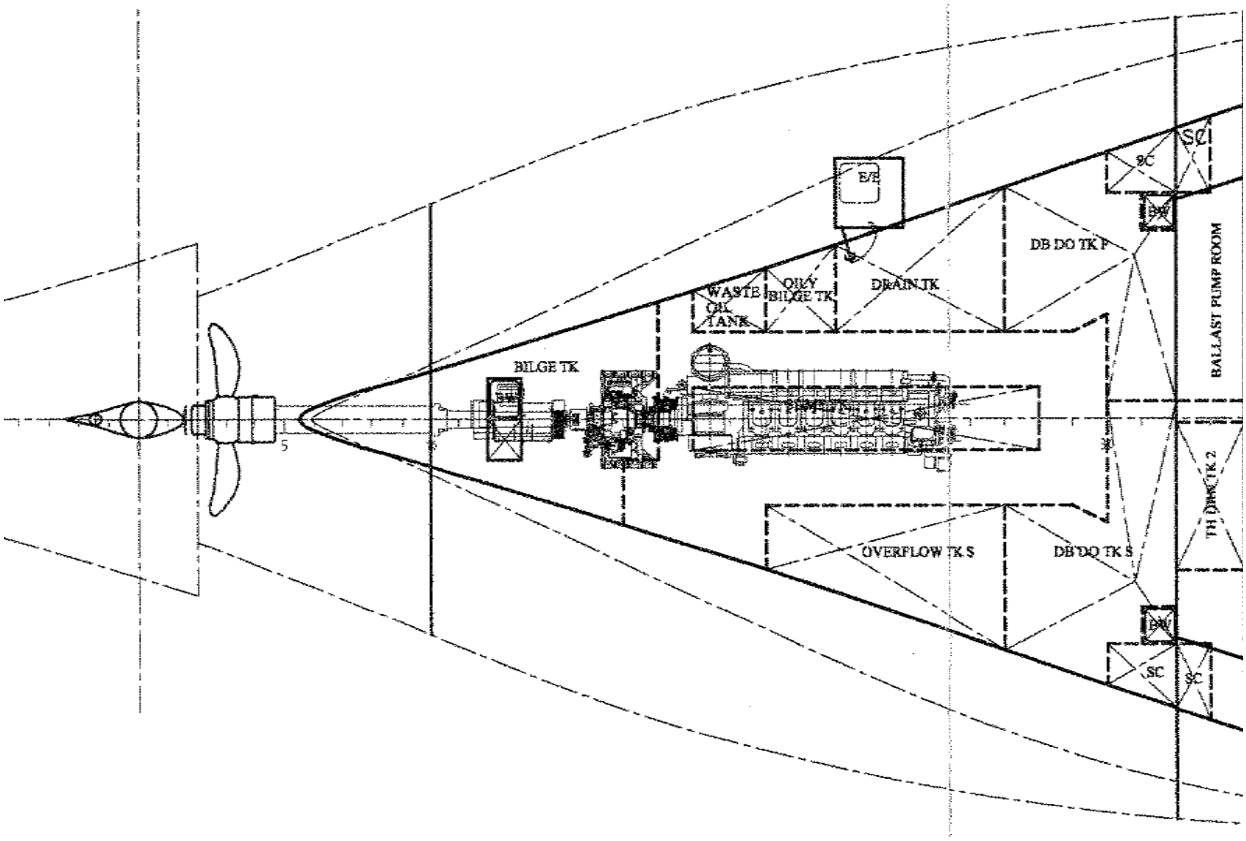

Figure 2. Bottom floor of the engine room

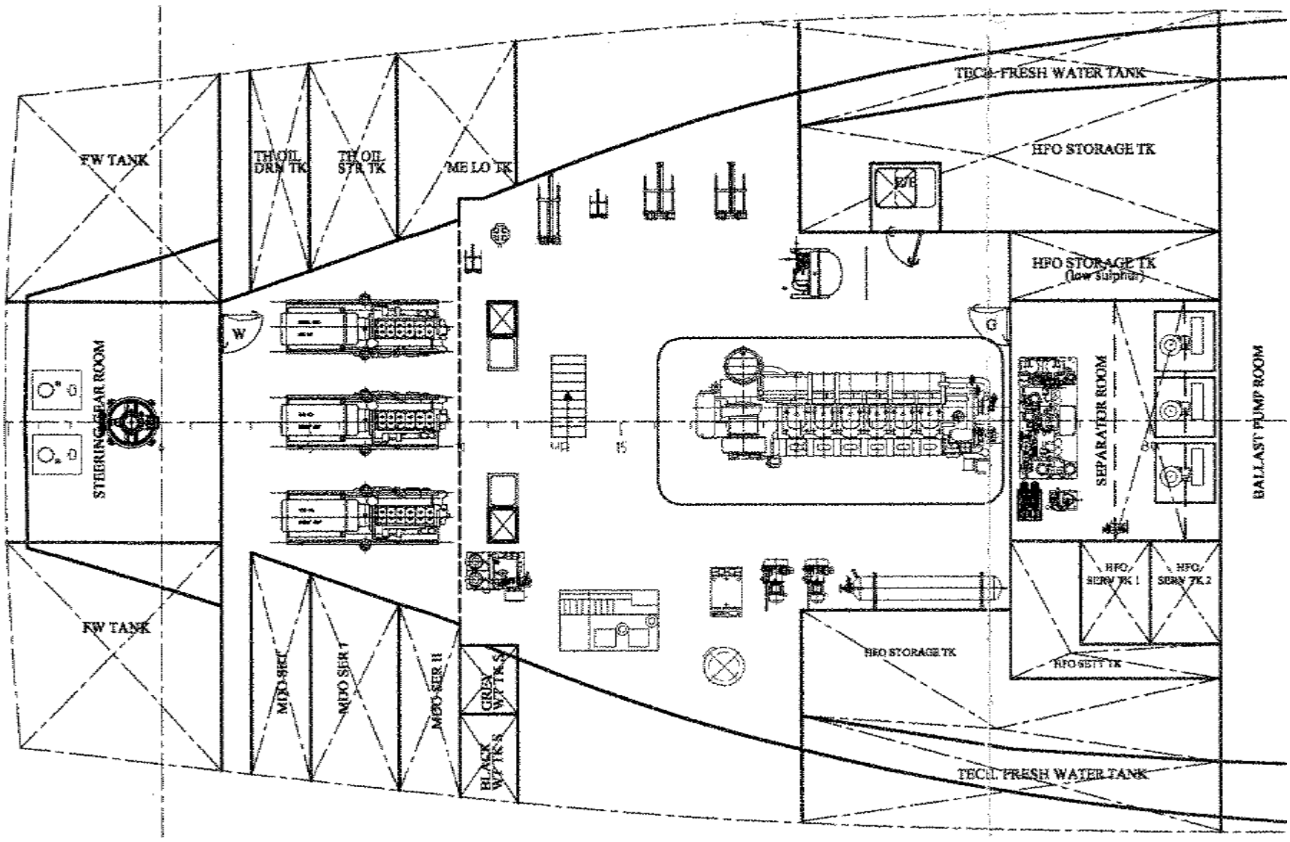

Figure 3. Second floor of the engine room

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	Elevsis	Constantza	616.7	69.5	8.87
6	Ravenna	Elevsis	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

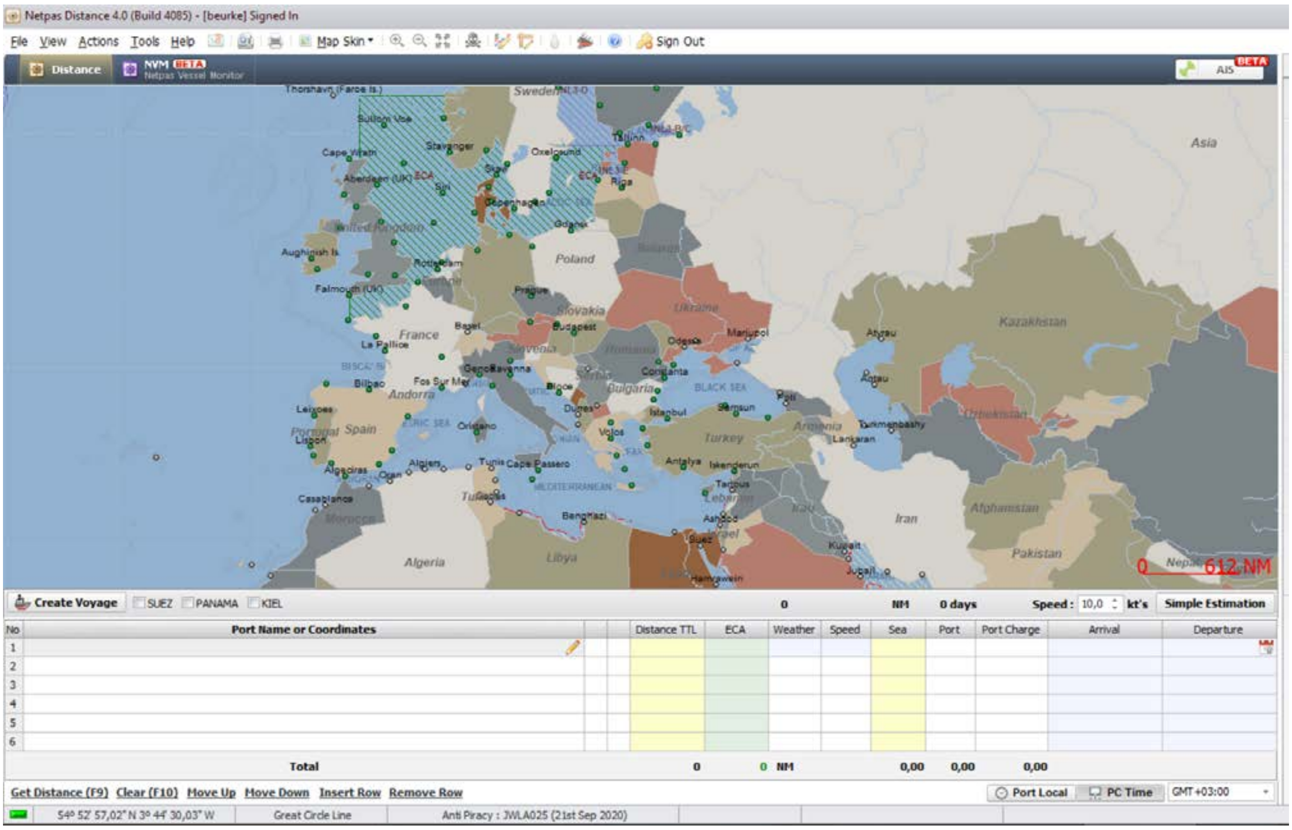

Figure 4. User interface of Netpas software

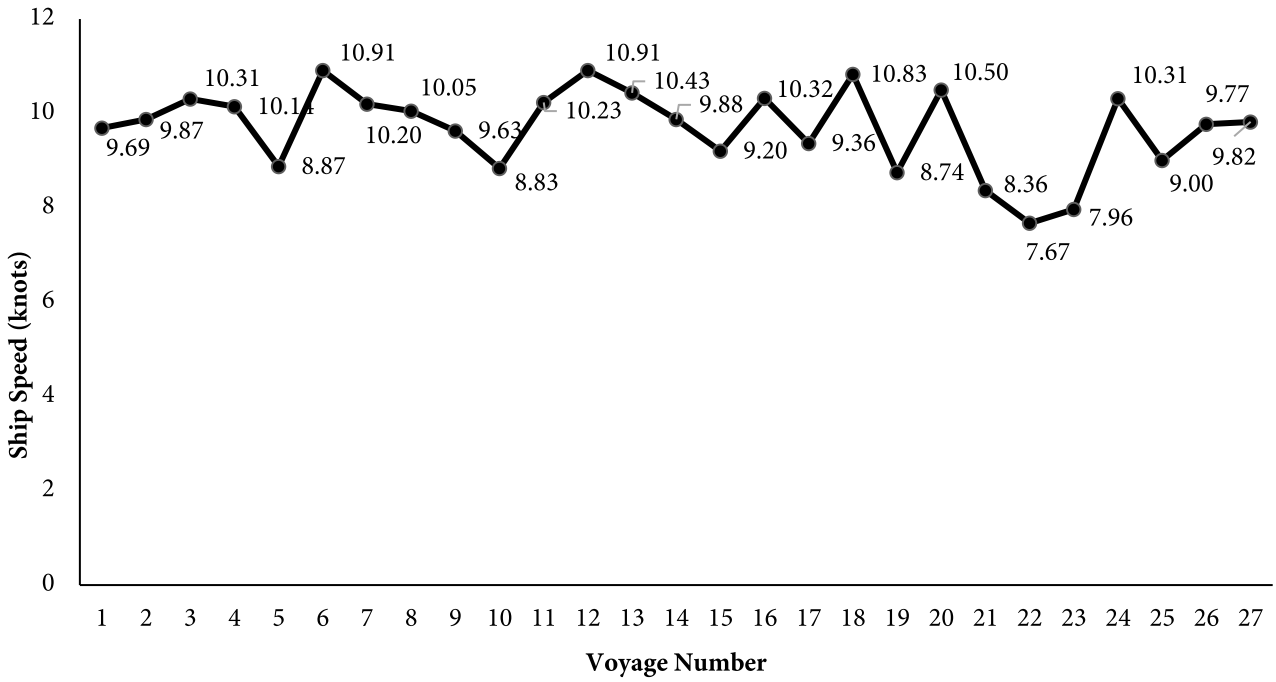

Figure 5. Average ships speed for each voyage

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_{actual}) and design power (P_{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_{actual}) and design speed (v_{design}) of the ship, prime the speed coefficient (α) (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.

$$Load\ Ratio\ (L_R) = P_{actual} / P_{design} = (v_{actual} / v_{design})^{\alpha} \quad (4.1)$$

Where P_{actual} becomes;

$$Pactual = (v_{actual} / v_{design})^{\alpha}\ x\ P_{design} \quad (4.2)$$

The SFOC actual can be calculated as following:

$$SFOCactual\ (g/kWh) = SFOCbase\ x\ SFOCratio \quad (4.3)$$

The $SFOC_{base}$ 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 $SFOC_{ratio,}$ and the relationship between them is given as follows (Dere and Deniz, 2019; Moreno-Gutiérrez et al., 2015):

$$SFOCratio\ (g/kWh) = 0.455L_R^2 - 0.71L_R + 1.28 \quad (4.4)$$

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

$$EFC\ (kg) = Pactual\ (kW) \times SFOCactual \left(\frac{g}{kWh}\right) \times Time\ (h) \times 10^{-3} \quad (4.5)$$

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:

$$CO2\ Emission\ (kg) for\ MCFC\ =\ 444.5\left(\frac{g}{kWh}\right)\ x\ Pactual(kW)\ x\ Time(h)\ x\ 10^{-3} \tag{4.6}$$

$$CO2\ Emission\ (kg)\ for\ MDO\ Diesel\ Engine\ =\ 3.206\ x\ EFC\ (kg) \tag{4.7}$$

$$CO2\ Emission\ (kg)\ for\ HFO\ Diesel\ Engine\ =\ 3.114\ x\ EFC\ (kg) \tag{4.8}$$

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

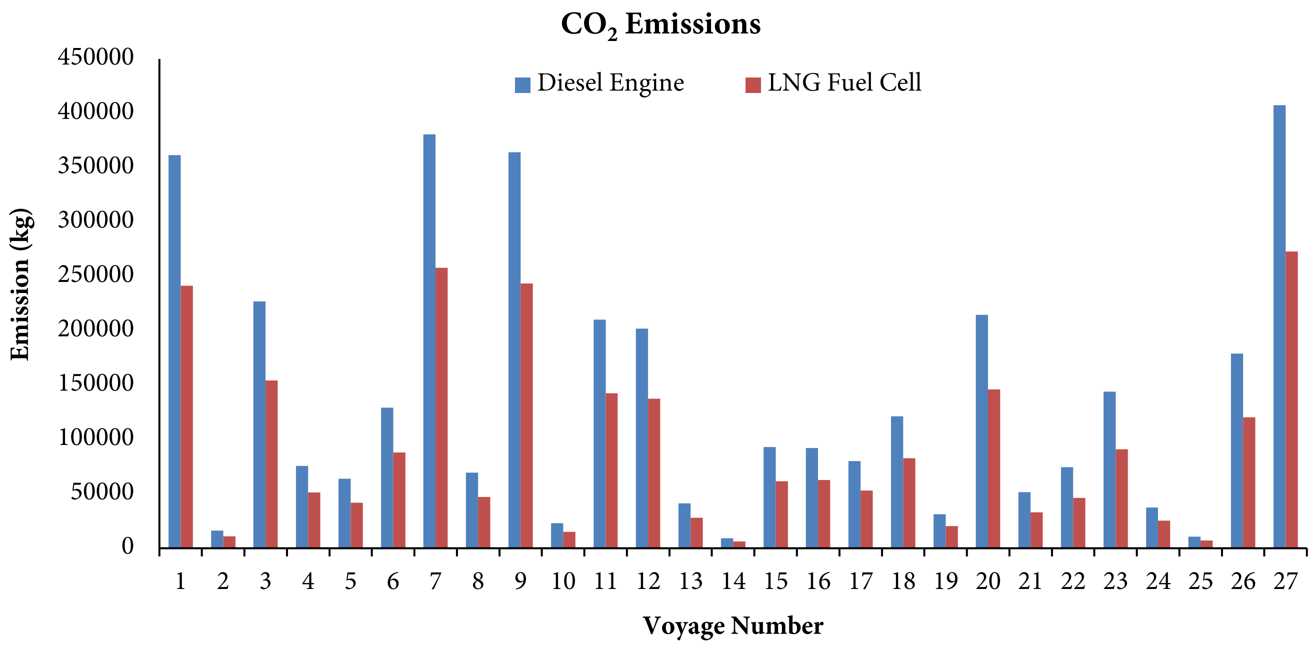

Figure 6. CO_2 emissions according to the fuel type and voyage number

The results show that more than 1200 tons of CO_2 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 CO_2 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.

$$Baseline = a\ \times\ b^{-c} \tag{4.9}$$

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).

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

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.

$$\frac{(\prod_{j=1}^{M} f_j) \times (\sum_{i=1}^{nME} P_{MEi} \times C_{FME} \times SFC_{ME}) + (P_{AE} \times C_{FAE} \times SFC_{AE}) + ((\prod_{j=1}^{M} f_j \times \sum_{i=1}^{nPTI} P_{PTI(i)} - \sum_{i=1}^{neff} f_{eff(i)} \times P_{AEeff(i)}) C_{FAE} \times SFC_{AE}) - \sum_{i=1}^{neff} f_{eff(i)} \times P_{eff(i)} \times C_{FME} \times SFC_{ME})}{f_i \times f_c \times f_l \times Capacity \times f_w \times V_{ref}} \quad (4.11)$$

Table 8. Parameters used in equation (4.11)

Parameter	Explanation
P_{MEi}	Main engine power
C_{FME}	Carbon content of fuel used in main engine
SFC_{ME}	Specific fuel consumption of main engine
P_{AE}	Auxiliary engine power
CF_{AE}	Carbon content of fuel used in auxiliary engine
SFC_{AE}	Specific fuel consumption of auxiliary engine
P_{PTI}	Power consumption of shaft motor
P_{AEeff}	Power of innovative technology
P_{eff}	Efficiency of the innovative technology
Capacity	Deadweight tonnage of the ship
V_{ref}	Ship speed
f_j	Correction factor to account for ship specific design elements
f_{eff}	Availability factor of innovative energy efficiency technology
f_i	Capacity factor for any technical limitation on capacity
f_c	Cubic capacity correction factor
f_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

NO_x Emissions

The case ship has an engine that satisfies IMO Tier II NO_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), the maximum allowable NO_x emission can be found 9.59 g/kWh. Therefore, NO_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_x decrease is calculated, totally. As expected, the main reason for NO_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_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_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_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_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% since 2015. Therefore, in this research both possible options are investigated in the meaning of sulphur oxide emission.

In this context, 2 different fuel emissions for diesel engine are calculated under acceptable limits for both the 2018 and 2020 years. The voyages in ECA for our case ship are already 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_x emissions are calculated according to formulas (4.15) and (4.16) where, 0.97553 is the fraction of fuel sulphur converted to SO_x and 2 is the ratio of molecular weight of SO_x and sulphur (IMO, 2015):

$$The\ maximum\ allowable\ NO_x\ emission\ (kg) = 44 \times n^{-0.23} \quad (4.12)$$

$$NO_x\ emission\ for\ diesel\ (kg) = 9.59\ \left(\frac{g}{kWh}\right) \times P_{actual}\ (kW) \times Time\ (h) \times 10^{-3} \quad (4.13)$$

$$NO_x\ emission\ for\ MCFC\ (kg) = 0.0045\ \left(\frac{g}{kWh}\right) \times P_{actual}\ (kW) \times Time\ (h) \times 10^{-3} \quad (4.14)$$

$$SO_x\ \left(\frac{g}{kWh}\right) = SFOC_{actual}\ \left(\frac{g}{kWh}\right) \times 2\ \times 0.97753 \times \%fuel\ sulphur\ fraction \quad (4.15)$$

$$SO_x\ (kg) = SO_x \left(\frac{g}{kWh}\right) \times P_{actual} \times Time\ x\ 10^{-3} \quad (4.16)$$

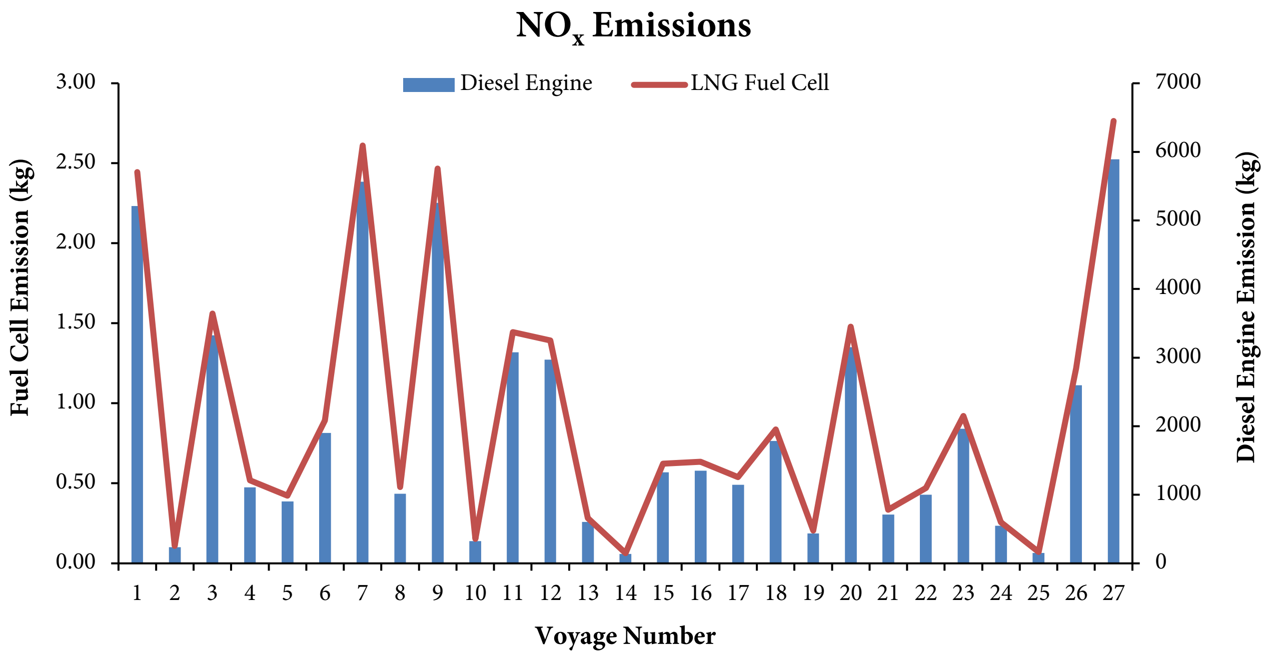

Figure 7. NO$_x$ emissions according to the fuel type and voyage number

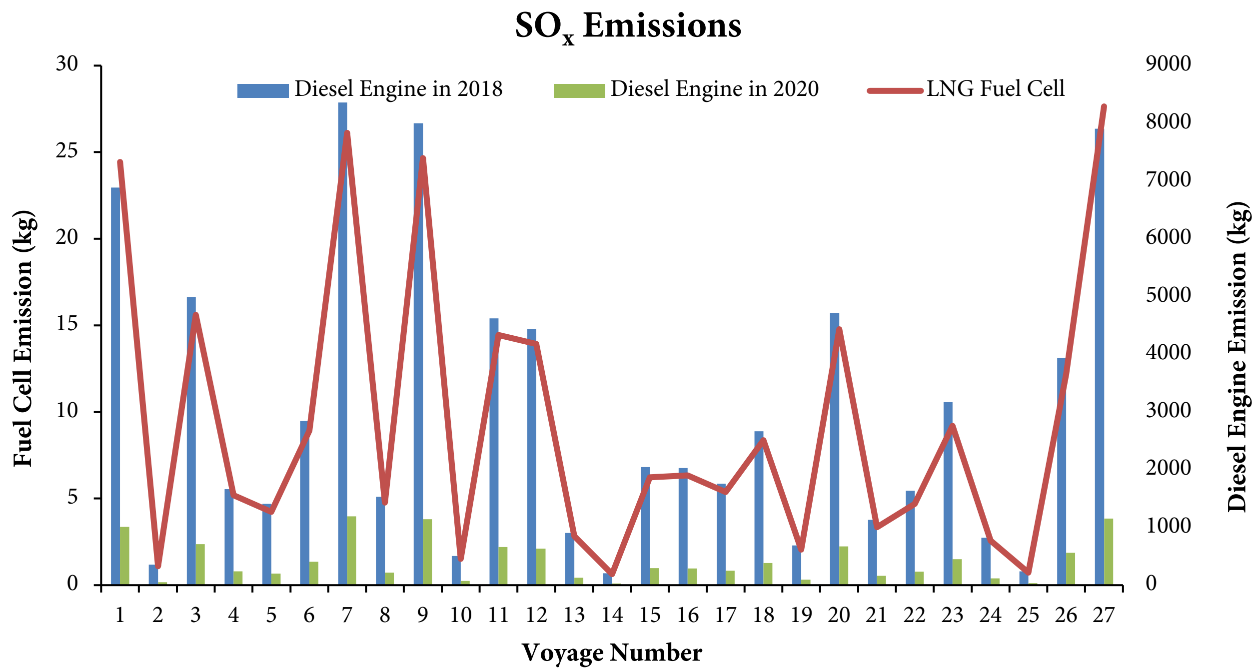

Figure 8. Total SO$_x$ emissions according to the fuel type and voyage number

In Figure 8, SO$_x$ 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$_x$ 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$_x$. 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):

$$PM(kg) = [1.35 + SFOC\ x\ 7\ x\ 0.02247\ x\ (SF - 0.0246)]\ x\ P_{actual}\ x\ Time\ (h)\ x\ 10^{-3} \quad (4.17)$$

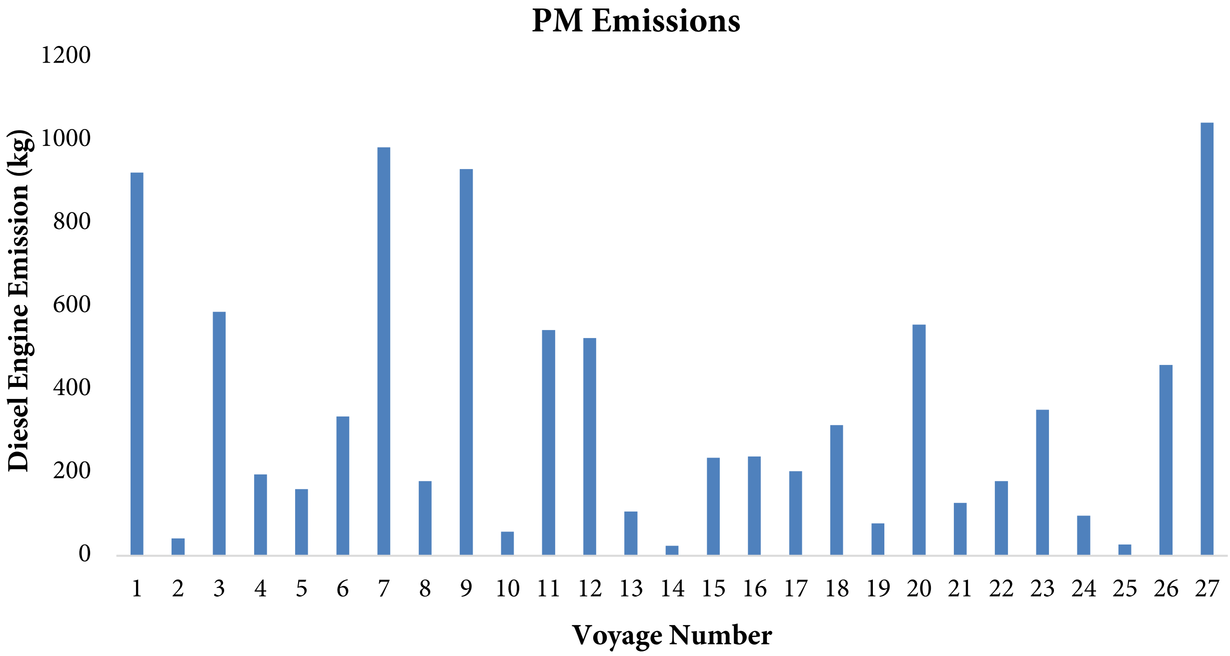

Figure 9. Total PM emissions according to the fuel type and voyage number

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 SO_x, PM, and NO_x and 33% of CO_2 emission reductions are calculated. Furthermore, 11402 kg of SO_x, 9506 kg of PM, 53668 kg NO_x and 1223 tons of CO_2 emissions is reduced just by one ship for 27 voyages in the Mediterranean Sea. The reduction at SO_x was expected due to LNG characteristics but in contrast, the reduction at CO_2 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.

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