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An environmental and economic analysis of methanol fuel for a cellular container ship

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ABSTRACT

In this study, the use of methanol is proposed as an alternative fuel to comply with the international maritime organization (IMO) emission regulations. Environmental and economic analysis of the methanol-diesel dual fuel engine is carried out. As a case study, cellular container ship is investigated. The results show environmental benefits for reducing NO_x, SO_x, CO, CO_2, and PM emissions by 76.78%, 89%, 55%, 18.13%, and 82.56%, respectively. In order to reduce the dual-fuel cost to the cost of the diesel fuel at maximum continuous rating (MCR), the ship speed should be reduced by 28%. In addition, the currently operated diesel engine uses selective catalytic reduction method (SCR) to comply with the IMO emission regulations. Combining the benefits of ship slow steaming and the saved SCR costs, the cost-effectiveness of dual-fuel engine for reducing NO_x, CO, and CO_2 emissions will be 385.2 \$/ton, 6548 \$/ton, and 39.9 \$/ton, respectively.

1. Introduction

One of the main goals of the international maritime organization (IMO) is to mitigate and control of the shipboard emissions. According to the third IMO-GHG study 2014, the average annual fuel consumption for all worldwide ships is 300 million tons (IMO, 2014b). In 2012, the annual sulfur oxides (SO_x) and nitrogen oxides (NO_x) emissions were 10.2 million tons and 19.0 million tons, which accounts for 13% and 15% of the global SO_x and NO_x emissions, respectively. In addition, the particulate matter (PM), carbon monoxide (CO), and carbon dioxide (CO_2) were 1.4 million tons, 936 thousand tons, and 949 million tons, respectively (Boden et al., 2013; Peters et al., 2013; IMO, 2014b). In order to reduce these emissions, IMO introduced regulations for limiting NO_x, SO_x, PM, and CO_2 emissions (Ammar and Seddiek, 2017; Dragović et al., 2018). From the beginning of the 2012, Tiers I, II, and III have been entered into force to reduce NO_x emissions. SO_x and PM emissions are reduced by limiting the sulfur content of the used fuel especially in the emission control areas (ECA) (Murena et al., 2018; Welaya et al., 2013; Welaya et al., 2014b; Welaya et al., 2014a). Finally, ship energy efficiency management plan (SEEMP), energy efficiency design and operational indexes were entered into force from January 2013 to limit CO_2 emissions (Agnolucci et al., 2014; IMO, 2015; IMO, 2014a; IRCLASS, 2013; GL, 2013).

In addition to the fossil fuel emission problem, the available reserves and its depletion are another important issue. Fig. 1 shows the international production and consumption of liquid fuels and the remaining crude oil reserves according to the year 2017. According to the current estimations of the petroleum exporting countries (OPEC), the total world proven oil reserves are 1,482.77 billion barrels (OPEC, 2018). OPEC member countries own 81.89% of these reserves. On the other hand, the global petroleum and liquid fuels consumption was 98.4 million barrel per day (b/d) in 2017 according to the US energy information administration (EIA).

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Nomenclature

ACR	annualized capital cost recovery, \$/year
AE_R	annual emission reduction, tons/year
AMC	annual maintenance and operating costs, \$/year
C_i	initial capital cost, \$
CE_{eff}	annual cost-effectiveness, \$/ton
E	engine emission factor, kg/kWh
E_F	fuel emission factor, ton/kWh
E_Q	emission quantity, ton
h	engine running time, h
i	annual interest rate, %
L_e	engine load percent
n	expected remaining ship working-years, year
P	engine power at maximum continuous rating, kW
SFC	specific fuel consumption, g/kWh
x	fuel percent in case of using DFE

Subscript

D	diesel engine
DFE	dual fuel diesel engine
ME	methanol engine

Abbreviations

CO_2	carbon dioxide
DFE	dual fuel diesel engine
HC	hydrocarbon emissions
IMO	International Maritime Organization
MCR	maximum continuous rating
MDO	marine diesel Oil
NO_x	Nitrogen Oxides Emissions
PM	Particulate Matter
S	Sulfur
SCR	Selective Catalytic Reduction
SO_x	Sulfur Oxides Emissions
SR	ship speed reduction ratio

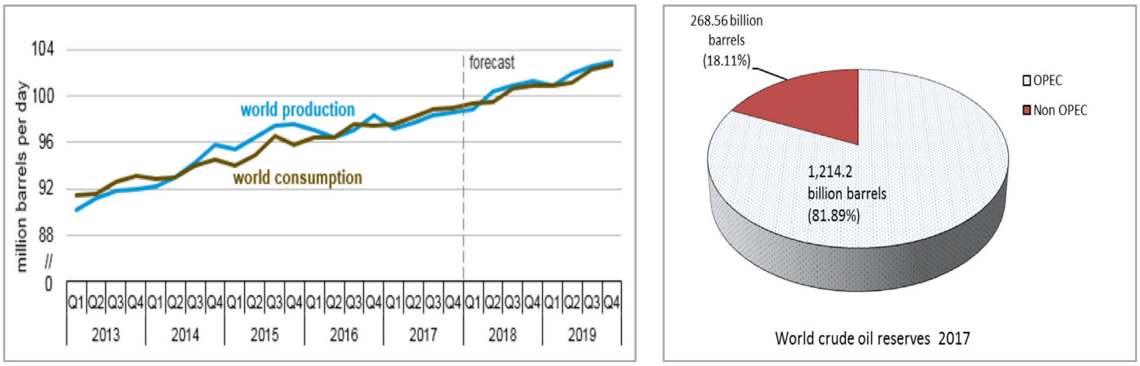

Fig. 1. Global liquid fuel oil production and consumption balance (2013–2019).

They expect that the consumption will exceed the production in 2018 and 2019 (EIA, 2018). Therefore, searching for alternative marine fuels will be necessary to solve the problem of fossil fuel depletion.

One of the alternative marine fuels which can be produced from renewable energy sources is the methanol fuel. It can be used to reduce the diesel engine emissions to comply with the required IMO 2020 regulations. Therefore, IMO invited the international organization for standardization (ISO) to develop a standard for methanol as a marine fuel in 26 September 2017 (IMO, 2017; Methanol Institute, 2018). Table 1 shows a comparison between methanol, diesel, and alternative marine fuels (Deniz and Zincir, 2016; Yao et al., 2008; Cheng et al., 2008; Ammar and Alshammari, 2018; Ammar and Seddiek, 2017; El Gohary and Ammar, 2016; El Gohary et al., 2014; Elgohary et al., 2014). Methanol is a sulfur free, toxic, corrosive, and liquid fuel in the ambient state. It requires up twice space as marine diesel oil (MDO). According to MAN engines, corrosive level and formaldehyde generation of the methanol fuel can be easily solved in the currently operated two and four stroke marine diesel engines (MAN, 2014).

Table 1
Comparison between methanol and different marine fuel properties.

Property	Methanol	Ethanol	Hydrogen	LNG	Diesel
Density (kg/m^3)	798	794	0.0838	450	833–881
Carbon contents (wt %)	37.49	74.84	0	75	86.88
Sulfur content (wt %)	0	0	0	0	varies
Net heating value (MJ/kg)	20.1	27	119.9	46–50.2	42.5
Air-fuel ratio (stoichiometric)	6.5	9.1	34.3	17.2	14.5
Flash temp. (°C)	11	17.2	−253	−136	55
Flame temp. (°C at 1.0 bar)	1890	1920	2045	1960	2054

Methanol has a low flash temperature of 11 °C, which is not complied with the safety of life at sea convention (SOLAS). However, using double wall design of methanol components can solve this problem, according to MAN Diesel & Turbo. They have developed two stroke methanol-diesel dual fuel engines for seven new-built methanol-transporting tankers (MAN, 2014). Fig. 2 shows the prices for marine gas oil (MGO) fuel and the energy equivalent methanol fuel (Methanex, 2018; Bunkerworld, September 2018; Chesko and Jaramillo, 2018). Based on 2018 fuel prices, the equivalent methanol fuel price per ton is higher than MGO.

The aim of the present paper is to study the environmental benefits for methanol as a marine fuel. In addition, the economic use of methanol-diesel dual fuel engine onboard ships is investigated. The costs of diesel engine conversion to dual-fuel engine are calculated. Diesel and methanol fuels consumption are determined based on the economic selection of the input methanol fuel percent. Finally, the cost-effectiveness for each emission reduction percentages after using methanol fuel is assessed. As a case study, a cellular container ship is investigated.

2. Environmental and economic modeling

The total emission quantity of a ship during one trip (E_Q) in tons is the summation of the emission quantities during standby, maneuvering and cruise modes of operations. These emission values depend on the engine power (P) in kW, running hours (h), load factor (L_e), and the fuel emission factor (E_f) in ton/kWh (Farooqui et al., 2013; Ammar and Seddiek, 2017). E_Q can be calculated using Eq. (1).

$$E_Q = P \cdot h \cdot L_e \cdot E_f \tag{1}$$

The slow speed diesel engine emission factors operated with MDO (0.1% S) at cruise are 17 g/kWh, 0.36 g/kWh, 0.19 g/kWh, 688.79 g/kWh, 1.4 g/kWh, and 0.6 g/kWh for NO_x, SO_x, PM, CO_2, CO and HC, respectively (ICF, 2009a). At low engine loads (%L_e), these values can be calculated using Eq. (2) except SO_x emission values can be calculated using Eq. (3), based on the specific fuel consumption (SFC) in g/kWh and sulfur percent (%S) (EEA, 2000). Table 2 (ICF, 2009a) shows the values of the coefficients (a, z, and b) used in Eqs. (2) and (3).

$$E_Q = a(\%L_e)^{-z} + b \tag{2}$$

$$E_{Q,SO_2} = a(SFC \times \%S) + b \tag{3}$$

For the case of using dual diesel-methanol fuels, the emission factor for the dual-fuel engine ($E_{Q,DFE}$) can be expressed using Eq. (4).

$$E_{Q,DFE} = x_D E_{Q,DE} + x_M E_{Q,ME} \tag{4}$$

where, x_D and x_M are the percentages of MDO and methanol fuels in the case of using dual-fuel engine (DFE), $E_{Q,DE}$ and $E_{Q,ME}$ are the emission factors for diesel and methanol engines. Emission factors for methanol engine in cruise mode are 2.16 g/kWh, 0 g/kWh, 0 g/kWh, 548.2 g/kWh, 0.54 g/kWh and 0.9205 g/kWh for NO_x, SO_x, PM, CO_2, CO and HC emissions, respectively (MAN, 2014).

From economic point of view, the annual capital cost recovery (ACR) for using methanol-diesel dual fuel engine can be calculated using Eq. (5) (Hunt and Butman, 1995).

$$ACR = C_i \times \frac{i(1+i)^N}{(1+i)^N - 1} \tag{5}$$

where, C_i is the initial capital cost value, N is the expected ship age after conversion, and i is the interest rate.

In addition, the annual cost-effectiveness for each pollutant emission reduction after using the dual-fuel engine (CE_{eff}) can be

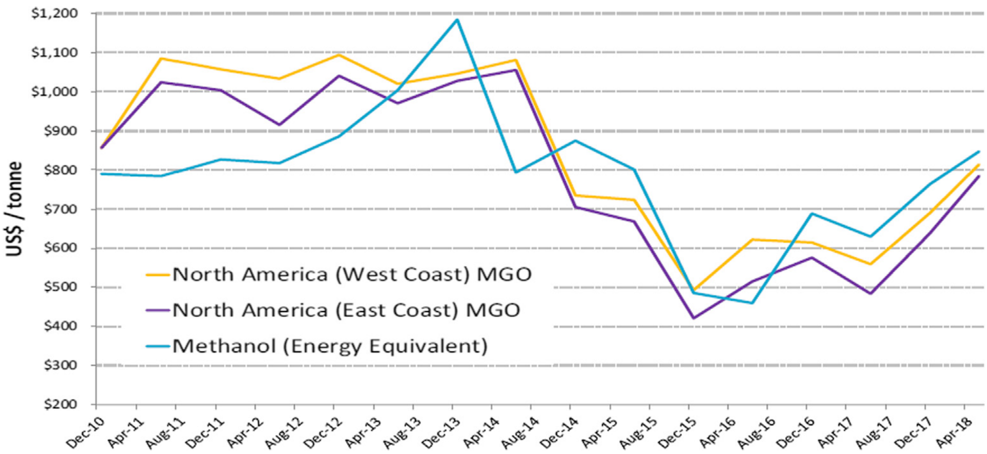

Fig. 2. Marine gas oil and equivalent methanol fuel prices.

Table 2
Coefficients of emission quantities algorithm.

Coefficient	NO_x	SO_2	PM	CO_2	CO	HC
a	0.1255	2.3735	0.0059	44.1	0.8378	0.0667
z	1.5	n/a	1.5	1.0	1.0	1.5
b	10.4496	−0.4792	0.2551	648.6	0.1548	0.3859

calculated using Eq. (6). This includes calculating ACR, annual maintenance and operating costs (AMC) and annual emission reduction (AE_R) in tons/year (ICF, 2009b; Ammar, 2018; Ammar and Seddiek, 2018).

$$CE_{eff} = \frac{ACR + AMC}{AE_R} \tag{6}$$

3. Case study

Al Dhail is a cellular container ship owned to the United Arab shipping company limited, Dubai branch. The ship was built in 2016 with IMO number of 9,732,307 and Majuro port of registration under the authority of the government of the republic of Marshall Islands. Table 3 shows the main technical data of the ship (Marine Traffic, 2018; Hapag-LIoyd, 2018; FleetMon, 2018). The container ship is propelled by a slow speed marine diesel engine (Hyundai-Man B&W 9590 ME-C) which operated with marine diesel oil MDO (0.1% sulfur). The engine output power is 37,620 kW at 72 rpm. Its load factors are 85%, 20%, and 5% during cruise, maneuvering, and standby modes, respectively. Engine room is arranged to be aft, with deckhouse and accommodation forward. The engine shaft is connected to a gearbox (GB) which operates a fixed pitch propeller and a shaft generator (SG) with output power of 5,500 kW. Additionally, four auxiliary engines (AE), rated 4,320 kW for each engine, are used to provide the electric power when the main engine is not in operation, or in case of SG failure.

4. Results and discussion

The results include the use of methanol fuel as the main fuel for a cellular container ship. The environmental benefits of methanol-diesel dual-fuel engine are discussed based on the fuel consumption and the emission calculations. In addition, the economic benefits of the dual-fuel engine are analyzed through calculating the fuel and the initial payment costs for the dual-fuel engine conversion. Finally, the cost-effectiveness for the emission reduction using methanol fuel is analyzed.

4.1. Environmental benefits of the conversion process

According to the published experimental results, methanol engine efficiency is equal to or even higher than that for traditional fuels (Pan et al., 2015; Andersson and Salazar, 2015; Olah, 2012; MAN, 2014). Therefore, the current study assumes that the efficiency of the converted dual methanol-diesel engine will be the same as the diesel engine efficiency. The first step in evaluating the environmental benefits of methanol dual-fuel engine is to calculate the specific emission factors. Using Eq. (4), the emission factors for the dual-fuel engine can be calculated at different methanol fuel percentages. In order to use methanol fuel percentages above 50% in the dual-fuel engine, diesel fuel injection is preferred to be divided into pre- and main injection portions, according to the experimental data published by (Sarjovaara et al., 2013). Fig. 3 shows the different emission rates of the dual-fuel engine at different methanol substitution percentages. As the methanol percent increases, NO_x, SO_x, CO, CO_2 and PM emissions are reduced.

Table 3
Main data of Al Dhail container ship.

Ship type	Cellular container ship
Length overall, m	368.52
Length between perpend., m	352
Moulded draft, m	15.521
Moulded breadth, m	51
Moulded depth, m	30.35
International gross tonnage, ton	153,148
International net tonnage, ton	64,695
Container capacity, TEU	14,993
Service speed, knots	25 at MCR of 37,620 kW
Main engine type	Hyundai-MAN B&W 9590 ME-C 10.2
Power (MCR)	37,620 kW at 72 RPM
Shaft generator/motor power, kW	5,500 kW
Average trip time, days.	66
Number of trips per year	5.0

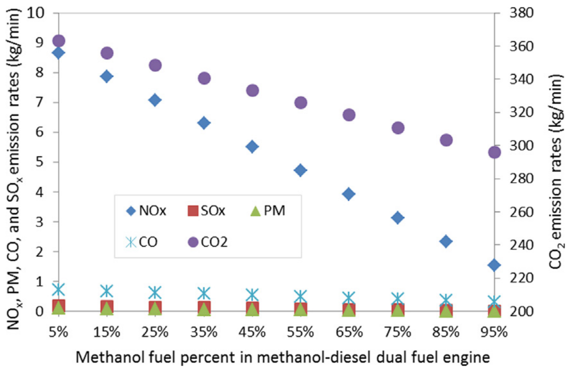

Fig. 3. Different emission rates at various methanol percentages.

SO_x and NO_x emission rates in kg/min during one trip can be calculated for diesel and dual-fuel engines based on the diesel and methanol emission factors as shown in Figs. 4 and 5. In addition, IMO 2016 and 2020 emission-limit rates for NO_x and SO_x can be predicted based on engine speed (rpm) and fuel sulfur content (0.5%), respectively. It can be noticed that, SO_x emissions for the current engine are compliant with the current and the future IMO limits. This is because that the ship uses MDO with (0.1% S). In addition, SO_x emission rates in kg/min during maneuvering are lower than cruise mode while the emission factors in g/kWh are increased. This is because of the increased specific fuel consumption and the reduced engine efficiency at low engine loads (EPA, 2000).

In contrast, the current NO_x emission rates (9.06 kg/min) of the diesel engine must be reduced to the accepted IMO limits (2.039 kg/min). For dual-fuel engine (89% methanol and 11% MDO), NO_x emission rates (2.021 kg/min) will be compliant with the required IMO rates. During maneuvering, the engine output power and the NO_x emission rates in kg/min decrease while the emission factors in g/kWh increases compare with the cruise mode. This is because of the reduced engine efficiency and the increased specific fuel consumption during maneuvering mode (ICF, 2009a; Ammar and Seddiek, 2017). Therefore, dual-fuel engine (11% MDO (0.1% S) and 89% methanol) emission rates will comply with the current and the future NO_x and SO_x emission regulations.

To evaluate the environmental benefits for the selected dual-fuel engine with 89% methanol substitution percent, emission factors in g/kWh should be calculated. Table 4 presents the emission factors for the dual-fuel engine at ship cruise and during maneuvering modes. It can be noticed that emission factors are increased during maneuvering mode compared with the cruise mode because of the same reason explained for NO_x and SO_x emission rates.

The environmental effects of dual-fuel engine are clear when compared with the diesel engine as shown in Fig. 6. For the current case study, the emission rates for slow speed diesel engine operated by MDO (0.1% S) are 9.06 kg/min, 0.192 kg/min, 0.101 kg/min, 367.1 kg/min, and 0.746 kg/min for NO_x, SO_x, PM, CO_2, and CO emissions, respectively. These rates are reduced after applying dual-fuel engine (89% methanol and 11% MDO) to 2.02 kg/min, 0.021 kg/min, 0.011 kg/min, 300.4 kg/min, and 0.338 kg/min with reduction percentages of 76.78%, 89%, 82.56%, 18.13%, and 55.02%, respectively.

On the other hand, it is important to calculate the fuel consumption for the case study for both the diesel and the dual-fuel engines. This is essential for determining the required methanol storage tanks which are required to operate the ship in dual fuel mode. Table 5 shows the calculated fuel consumption for the case study taking into account that the required methanol fuel tanks are twice that of the replaced diesel fuel tanks (Deniz and Zincir, 2016). The proposed dual-fuel engine will operate with 89% methanol and 11% MDO. The average trip time is 66 days with 5.0 trips annually is used for calculating the annual fuel consumption quantities based on the data collected from the United Arab Shipping Company that owns the ship. (see Table 6)

Using Table 5, the different emissions values for the diesel and dual-fuel engines can be calculated for the case study as shown in

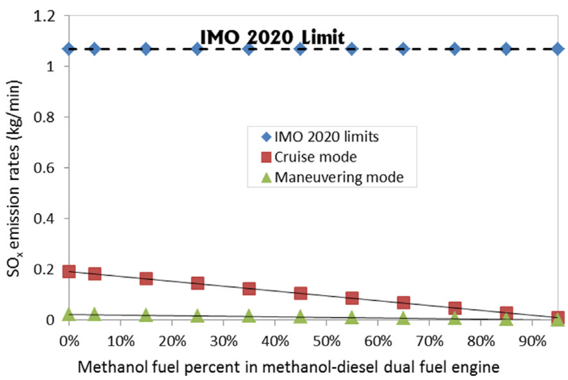

Fig. 4. SO_x emission rates at various methanol substitution percentages.

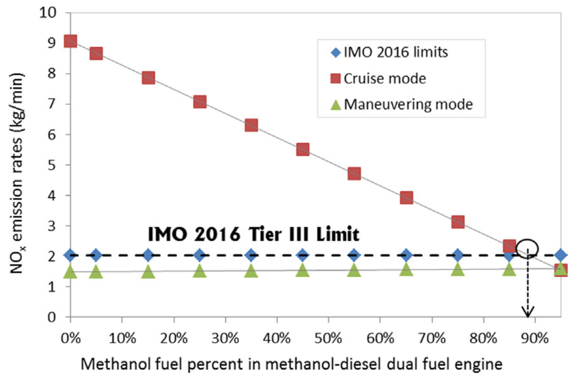

Fig. 5. NO_x emission rates at various methanol substitution percentages.

Table 4
Calculated dual-fuel engine (89% Methanol and 11% MDO) emission factors.

Emission factor (g/kWh)	NO_x	SO_x	PM	CO_2	CO	HC
At cruise	3.792	0.039	0.021	563.70	0.634	0.885
During maneuvering	12.610	0.019	0.835	727.50	1.101	unknown

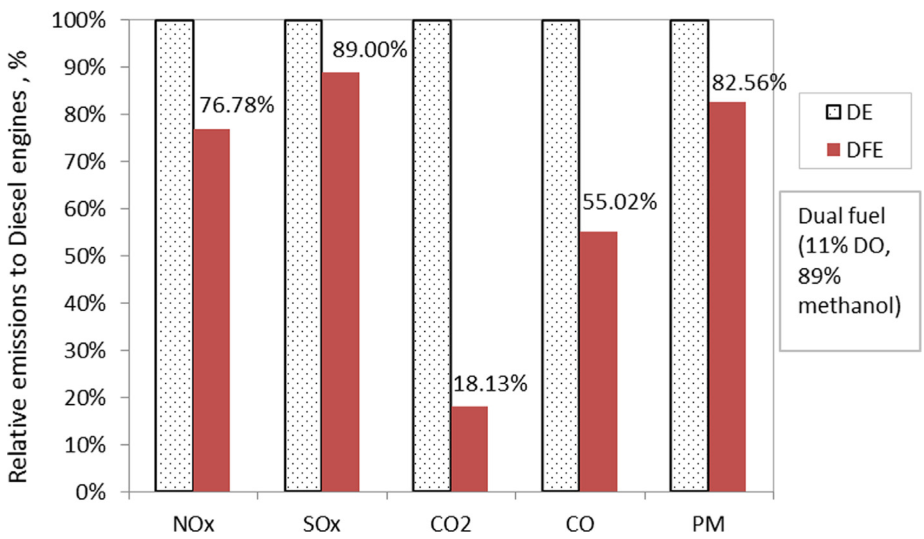

Fig. 6. Emission reduction percentages for dual methanol-diesel engine.

Table 5
Al Dhail container ship main engine fuel consumptions.

Fuel consumption (m^3)	Diesel engine	Dual-fuel Engine (89% methanol)	
	MDO (0.1%S)	Methanol	MDO (0.1%S)
Per trip	11,387	19, 918	1,428
Per year	56,936	99,589	7,142

Table 6. The annual NO_x, SO_x, CO, CO_2 and PM emissions are reduced by 76.78%, 89%, 55%, 18.13%, and 82.56%, respectively after using dual-fuel engine with 89% methanol. The highest emission reduction rate is the CO_2 because of the lower carbon content in methanol fuel compared with marine diesel oil.

Table 6
Environmental analysis of the Al Dhail cellular container ship.

Emission type	Engine mode	Emissions/trip (t)	Emissions/year (t)	Emission reduction (t/year)
NO_x	Diesel engine	791.4	3,957	
	DFE engine	183.7	918.7	3,038.3
SO_x	Diesel engine	16.7	83.52	
	DFE engine	1.837	9.18	74.34
CO	Diesel engine	64.97	324.9	
	DFE engine	29.22	146.1	178.8
CO_2	Diesel engine	32,344	161,722	
	DFE engine	26,480	132,402	29,320
PM	Diesel engine	8.981	44.9	
	DFE engine	1.566	7.83	37.07

4.2. Economic analysis of the conversion process

In this section, the economic aspects for the diesel engine conversion to the dual-fuel engine are discussed. The annual fuel costs for both engines are calculated. In addition, a proposed solution for the increased dual-fuel costs compared with the diesel fuel costs is investigated. Finally, the cost-effectiveness for NO_x, CO, and CO_2 emission reductions using dual-fuel engine are evaluated. One of the main advantages of the methanol fuel is that it is very similar to marine diesel fuels due to its liquid state. The currently used diesel fuel infrastructure can be used for methanol fuel with minor modifications based on its low flashpoint (Andersson and Salazar, 2015). Therefore, the current study assumes the same costs for diesel and methanol fuels bunkering facilities. Table 7 reveals the annual fuel cost split for the dual-fuel and diesel engines. The calculations are based on the diesel and methanol fuel costs of 833 $/m^3$ and 601 $/m^3$ (Bunkerworld, September 2018; Methanex, 2018), respectively with 8.0 $/m^3$ for the bunkering prices (Ammar and Seddiek, 2017). Although, the methanol fuel price rate is lower than diesel by 38.6%, the total annual fuel consumption cost for the dual-fuel engine is higher than diesel fuel by 28.16%. This is because of the increased methanol fuel consumption compared with its equivalent diesel fuel.

In addition to the fuel price cost comparison, conversion, maintenance and operating costs for both engines should be assessed. From maintenance and operating points of view, the same or even longer interval periods are expected for methanol dual-fuel engine compared with diesel engines as it is a clean fuel (Chen et al., 2016; Huang et al., 2004; Li et al., 2013). The cost of engine conversion for the case study is 10.72 million dollars with a conversion rate of 285 $/kW (Andersson and Salazar, 2015; Stefenson, 2014; Deniz and Zincir, 2016).

4.3. Speed reduction for dual methanol-diesel engine

Based on the current diesel and methanol fuel prices, methanol engine conversion process cannot be economically justified. There are environmental and other benefits which should be taken into consideration. From the experimental data published by (Sarjovaara et al., 2013), methanol dual-fuel engines may suffer from knocking problems at high engine loads and it is preferred to use a common rail injection system especially at high methanol substitution percent. Therefore, reducing the dual methanol-diesel engine output power is proposed by the author to reduce both the fuel consumption and emissions. The first step in calculating the fuel consumption at a reduced engine load is to formulate the relation between fuel consumption at different engine load fractions. With the help of the main engine, Hyundai-MAN B&W 9590 ME-C 10.2, project guide and curve fitting technique, the correlation between fuel consumption at different engine loads can be deduced as shown in Fig. 7. The next step is to calculate the fuel consumption at the reduced ship speed. The change in the fuel consumption during each trip ($m_{f,t}$) due to slow steaming can be calculated using the cubic law of speeds (Stopford, 2009; Banawan et al., 2013; Chang and Wang, 2014; Ammar, 2018) as expressed in Eq.(7).

$$m_{f,t} = [m_{f,1} \cdot (SR)^3 + m_{f,2}] \cdot \frac{T}{24} \tag{7}$$

where, $m_{f,1}$ and $m_{f,2}$ are the main and auxiliary engines fuel consumption per day; SR is the ship speed reduction ratio; and T is the

Table 7
Annual cost of fuel consumption for diesel and dual-fuel engine.

Cost item	Prices in (millions US$/year)	
	Diesel engine	DFE
Diesel oil	47.430	5.949
Diesel oil bunkering	0.455	0.057
Methanol	0	59.850
Methanol bunkering	0	0.797
Total fuel cost	47.885	66.653

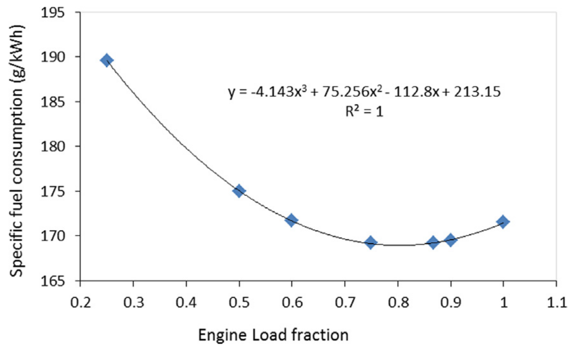

Fig. 7. The specific fuel consumption correlation for the main engine.

new trip time at the reduced ship speed.

Fig. 8 shows the effect of the reduction of the ship speed on the cost of the diesel and the equivalent dual methanol-diesel fuels cost. At ship speed of 25 knots (MCR), the annual diesel fuel consumption for the diesel engine is 47,826 ton/year with a cost of 47.88 million $/year. The equivalent fuel cost using the dual-fuel engine is 66.65 million $/year. In order to reduce the equivalent dual-fuel cost to the diesel fuel cost at MCR, the operational ship speed should be reduced from 25 knots to 18 knots with a speed reduction ratio (SR) of 28%.

Reducing the fuel consumption at the reduced ship speed will save in the required fuel storage tanks as shown in Fig. 9. Using dual methanol engine will increase the required fuel storage tanks volume by twice to its equivalent diesel storage tanks. This is because of the low energy content per kg for the methanol compared with the diesel fuel. At MCR, the diesel fuel storage tanks are 11,389 m^3 for the diesel engine. On the other hand, diesel and methanol fuel storage tanks will be 1,429 m^3 and 19,920 m^3, respectively after using dual-fuel engine. At ship speed of 18 knots, the dual-fuel engine storage volumes will be reduced to 994.3 m^3 and 14,343 m^3 for diesel and methanol fuels, respectively. These values are lower than that at MCR by 38.88%.

Although applying the dual methanol-diesel engine onboard the case study is an environmental friendly option and achieves the required IMO emission limits, the cost of the equivalent diesel engine fuel cost is still more economic. This is due to the difference in the fuel prices and the energy content between the two fuels. In addition, the dual-fuel engine will be economically equivalent to the currently used marine diesel engine with the attached selective catalytic reduction (SCR) system for reducing NO_x emissions to the accepted IMO limits. SCR method reduces the NO_x emissions by 3561 ton/year, with a reduction percent of 90%. The initial cost for installing the SCR is 1.881 million dollars for the case study with an installation rate of 50 $/kW (INTERTANKO, 2007). The annual maintenance and operating costs are 268,189 $/year and 1,117,000 $/year with average cost rates of 0.9 $/mWh and 3.75 $/mWh, respectively (INTERTANKO, 2007; Ammar and Seddiek, 2017). The total annual cost for installing SCR at different interest rates of 5%, 10%, and 15% is shown in Fig. 10. The annual costs are planned over the remaining 26 years of ship operation assuming the average ship age is 28 years (Mikelis, 2008; Ammar and Seddiek, 2018).

On the other hand, the average methanol-diesel dual fuel engine conversion cost is 285 $/kW (Andersson and Salazar, 2015; Maritime Knowledge Centre, 2017). Using Eq. (5), the annual cost for the capital money recovery can be calculated, as shown in Fig. 11, at different interest rates. The annual cost required for the capital money recovery over the remaining ship age of 26 years is 1.17 million dollars, at 10% interest rate. At ship speed of 18 knots, the fuel cost of the dual-fuel engine is equivalent to the diesel-engine fuel cost at MCR speed of 25 knots. From economic point of view, each knot reduction of the ship speed will reduce the ship profit by 6.9% (Eide et al., 2009; Ammar, 2018). In order to evaluate the economic benefits for the dual-fuel engine, the annual costs for using SCR system in the diesel engine should be taken into consideration. At interest rate of 10%, the total annual SCR costs are 1.59 million dollars as shown in Fig. 10. These costs will be saved when using dual methanol-diesel engines. Combining the benefits of the ship slow steaming and the saved SCR costs, the dual-fuel conversion costs will be paid back during the first 12 years of ship

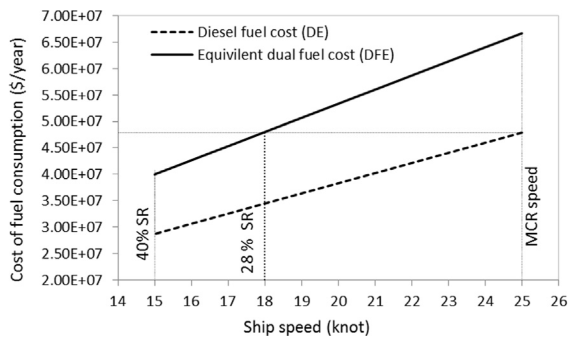

Fig. 8. The cost of diesel fuel consumption and its equivalent dual methanol-diesel fuels consumption at different ship speeds.

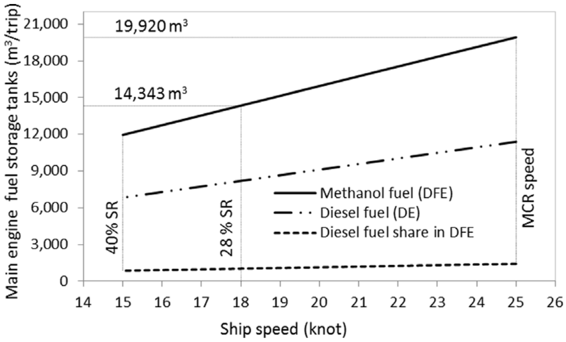

Fig. 9. Fuel storage tanks for diesel and dual-fuel engine at different ship speed.

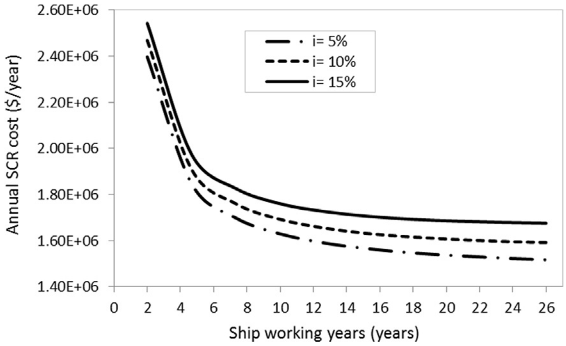

Fig. 10. Annual SCR costs for the main engine.

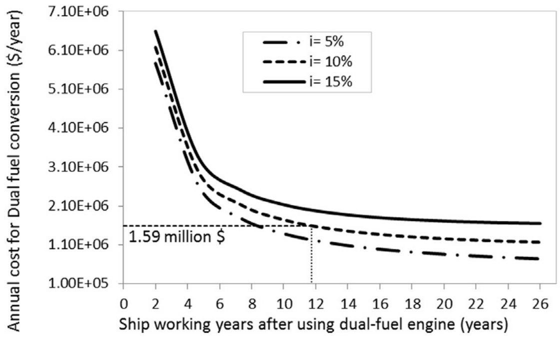

Fig. 11. Annual costs for dual-fuel engine conversion based on the saved SCR annual costs.

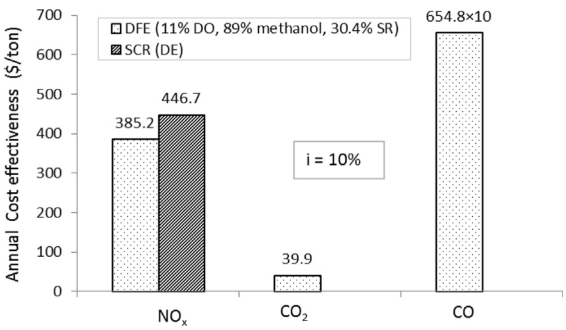

Fig. 12. Annual cost-effectiveness for emission reduction methods.

operation, using the saved SCR costs for the diesel engine without reducing ship profit, as shown in Fig. 11. In addition, the remaining 14 years of the operation will add more profit to the ship due to the save SCR costs.

Finally, the environmental benefits can be calculated in terms of the annual cost-effectiveness for each emission reduction. Fig. 12 shows the annual cost-effectiveness of reducing NO_x, CO, and CO_2 emissions. The most economic benefits for exhaust gas emission reduction after using methanol-diesel dual fuel engine is for reducing CO_2 emissions. It is reduced from 161,722 ton/year to 132,402 ton/year with cost-effectiveness of 39.9 $/ton. This reduction in CO_2 emissions will improve the greenhouse effect and both the energy efficiency design and operational indexes (EEDI and EEOI) (Ammar, 2018; Alisafaki and Papanikolaou, 2015; Agnolucci et al., 2014; Ančić and Šestan, 2015). In addition, NO_x and CO emissions will be reduced by 3,038.3 ton/year and 178.8 ton/year with cost-effectiveness of 385.2 $/ton and 6548 $/ton, respectively. Finally, the cost-effectiveness for NO_x emission reduction using SCR for the currently used diesel engine is 446.7 $/ton. This cost-effectiveness value is higher than that of the dual fuel engine by 13.8%.

5. Conclusions

The application of methanol dual-fuel engine for a cellular container ship has been investigated from environmental and economic points of view. The main conclusions from the current study are:

- From environmental point of view, using dual-fuel engine with 89% methanol and 11% marine diesel oil (MDO) will comply with the required IMO emission regulations. This will lead to reductions in NO_x, SO_x, CO, CO_2 and PM emissions by 76.78%, 89%, 55%, 18.13%, and 82.56%, respectively. In order to reduce the cost of the fuel for the dual engine to that of the diesel engine value at MCR, slow steaming by 28% is proposed. In addition, the currently used diesel engine applies selective catalytic reduction (SCR) method for reducing NO_x emissions by 90% to meet emission regulations.
- From economic point of view, the annual cost for recovering methanol dual-fuel engine conversion costs is 1.17 million $/year. The fuel and bunkering costs will be increased by 28.16% compared with the equivalent diesel engine costs, at MCR and 2018 fuel prices. The annual SCR costs which will be saved after using methanol-diesel dual fuel engine is 1.59 million $/year, at annual interest rate of 10%. Using the saved SCR costs, without reducing the ship profit, the cost of the engine conversion will be saved during the first 12 years of the dual-fuel engine operation.
- From cost-effectiveness point of view, using dual methanol fuel engine will reduce NO_x, CO, and CO_2 emissions with cost-effectiveness of 385.2 $/ton, 6548 $/ton, and 39.9 $/ton, respectively. In addition, the cost-effectiveness of NO_x emission reduction using SCR for the currently used diesel engine will be 446.7 $/ton which is less in economic benefit than that of the dual-fuel engine by 13.8%.

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