Chapter 4
Methanol as a Fuel for Marine Diesel Engines

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Abbreviations

A/F_S	Stoichiometric air–fuel ratio
CCS	Carbon capture system
CI	Compression ignition
COV IMEP	Coefficient of variation indicated mean effective pressure
DISI	Direct injection spark ignition
DME	Dimethyl ether
ECA	Emission control area
EEDI	Energy efficiency design index
EEOI	Energy efficiency operational indicator
EFTA	European Free Trade Association
EGR	Exhaust gas recirculation
EMSA	European Maritime Safety Agency
η_{GIE}	Gross-indicated efficiency
FuelMEP	Fuel mean effective pressure
HCCI	Homogenous charge compression ignition
HFO	Heavy fuel oil
IACS	The International Association of Classification Societies
IMEP	Gross-indicated mean effective pressure
IMO	International Maritime Organization
LHV	Lower heating value
LSMGO	Low-sulfur marine gas oil
MARPOL	International Convention for the Prevention of Pollution from Ships
MEPC	Marine Environment Protection Committee

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MGO	Marine gas oil
MON	Motor octane number
MRV	Monitoring, reporting, verification
NaOH	Caustic soda
PFI-SI	Port fuel injection-spark-ignited combustion
PPC	Partially premixed combustion
PRR	Pressure rise rate
RCCI	Reactivity-controlled compression ignition
RON	Research octane number
SAMS	Scavenge air moisturizing system
SCR	Selective catalytic reduction
SEC	Specific energy consumption
SEEMP	Ship energy efficiency management plan
SI	Spark ignition
SOFC	Solid oxide fuel cell
SVO	Straight vegetable oil
UNCTAD	The United Nations Conference on Trade and Development
WHRS	Waste heat recovery system

4.1 The Status of the Maritime Transportation

The transportation sector is indispensable for the mobility of people and goods worldwide. It connects people and provides persons or goods to reach the farthest destination of the world. Maritime transportation is an essential piece of the transportation sector and constitutes a major part of worldwide trade. 90% of the worldwide trade (Deniz and Zincir 2016), 90% of the outer freight, and 40% of the inner freight of the European Union (Fan et al. 2018) have been done by maritime transportation. According to 2019 data of the United Nations Conference on Trade and Development (UNCTAD), 96,295 ships are in operation which is equal to 1.97 billion deadweight tons (dwt) (United Nations Conference on Trade and Development (UNCTAD) 2019). Also, it is indicated that the annual maritime transportation volume growth was 2.6% in 2019, and it is estimated that an annual average growth rate will be 3.4% for the period 2019–2024.

On the other hand, maritime transportation has an important share of worldwide emissions. International Maritime Organization (IMO) states that maritime transportation consumes 300 million tons of fuel annually and leads to 938 million tons of CO_2, 19 million tons of NO_X, 10.2 million tons of SO_X, 1.4 million tons of PM, and 936 thousand tons of CO emissions in 2012 (International Maritime Organization (IMO) 2014). At a study of European Energy Agency (EEA) (2019), the maritime transportation has the contribution of 20.98% of the worldwide NO_X emissions, 11.80% of the worldwide SO_X emissions, 8.57 and 4.63% of the worldwide PM2.5 and PM10 emissions, respectively, and lastly, 1.94% of the worldwide CO emissions.

The status of maritime transportation was given in this section. Maritime transportation is an integrated part of global trade, and it is expected that the trade volume will be in the growing trend for the near future. It also means that the fuel consumption and engine emissions will be in increasing trend. To overcome this issue, international maritime emission rules and regulations are stricter day by day. The next section introduces rules and regulations about CO_2, NO_X, SO_X, and PM emissions to control and mitigate shipboard emissions.

4.2 International Maritime Emission Rules and Regulations

The fuel consumption and shipboard emissions have been in escalation since the ship number has increased year by year. Nowadays, shipboard emissions are the most important issue for maritime transportation. The International Maritime Organization (IMO) has been working on emission mitigation and control by implementing international maritime emission rules and regulations. The international maritime emission rules and regulations are becoming stricter day by day. There are rules and regulations for CO_2, NO_X, and SO_X emissions. There are not any specific rules or regulations for PM emissions, but it has been regulated by the SO_X regulation. All rules and regulations about these emissions were addressed in the International Convention for the Prevention of Pollution from Ships (MARPOL), Annex VI—Regulations for the prevention of air pollution from ships (May 2005). This section is going to give detailed information about international maritime emission rules and regulations.

4.2.1 Carbon Dioxide Emission Rules and Regulations

The carbon content of the fuel is the reason for the CO_2 emissions. To achieve zero CO_2 formation as a combustion product, the fuel does not contain carbon atoms in its structure. Almost all maritime transportation fuels contain carbon atoms, and the CO_2 formation is inevitable. It is awaited that the CO_2 emissions will raise with 50–250% compared to the 2008 level (International Maritime Organization (IMO) 2014). However, the CO_2 emissions can be decreased by reducing fuel consumption of the main engine and auxiliary engines of a ship or using low-carbon content fuels. Increasing energy efficiency on ships results in lower fuel consumption and reduced CO_2 emissions.

The Regulations on Energy Efficiency for Ships in MARPOL Annex VI regulates the CO_2 emissions from ships on and after January 1, 2013 (International Maritime Organization (IMO) 2011). The regulation aims to control and mitigate CO_2 emissions from the existing and new building ships. Two mandatory terms the energy

Table 4.1 EEDI reduction phases (Bazari 2016)

Phase	Year	Reduction amount (%)
0	2013–2015	0
1	2015–2020	10
2	2020–2025	15–20
3	2025–	30

efficiency design index (EEDI) and the ship energy efficiency management plan (SEEMP) and a voluntary term the energy efficiency operational indicator (EEOI) were defined by the regulation.

The EEDI is a measure for the new building ships. It aims to standardize and increase the use of energy-efficient engines and equipment on the new building ships. The vessel energy efficiency level is calculated by taking fuel consumption, fuel carbon content, ship speed, and the cargo carrying capacity of the ship (MAN 2014). Its unit is grams of CO_2 per ton-mile, and the lower value indicates a more efficient ship. There are "attained EEDI" and "required EEDI" in the regulation. The attained EEDI is the actual EEDI calculated for new building ships. And the required EEDI is the allowable maximum EEDI limit for the specific ship type. The required EEDI limit has decreased every five years phase by phase. Shipowners can use any technology which is suitable for their new building project for not exceeding the maximum EEDI limit. The phases are shown in Table 4.1.

The SEEMP was defined for the CO_2 emission control of the existing ships doing international maritime transportation. It is a mandatory plan for all ships, and it aims to encourage and increase the energy-efficient operation on the ships. The SEEMP contains measures such as optimizing ship speed, weather routing, trim optimization, hull and propeller cleaning, and using waste heat recovery system. Lastly, EEOI was introduced as a voluntary voyage-based calculation with the regulation. It aims to reduce CO_2 emissions emitted at a voyage (Zincir and Deniz 2016). The shipowners or operators can track their ship efficiency performance in grams of CO_2 per ton-mile basis. This voluntary term was the first building block of the mandatory rules, Monitoring, Reporting, Verification (MRV) Regulation and IMO Data Collection System (DCS). The CO_2 emission performance of a ship can be calculated by EEOI.

On July 1, 2015, the MRV Regulation entered into force by the European Union, Norway, and Iceland (Gl 2020). The regulation aims to record and control the annual CO_2 emissions of ships larger than 5000 GRT calling to the EU, Norway, and Iceland ports. The monitoring phase was started on January 1, 2018, by monitoring annual fuel consumption, voyage day, fuel carbon content, and CO_2 emission data of the ship. The second phase of reporting has started in 2019. The shipowners and operators have to submit their ship annual report to Thetis MRV application of the European Maritime Safety Agency (EMSA) (Gl 2017). The reporting phase encourages shipowners and operators to increase energy efficiency measures on a ship, reduce fuel consumption, or use lower carbon content fuel. And lastly, annual ship reports were verified and the verification document has been required by the port authorities after June 30, 2019.

Table 4.2 Greenhouse gas strategy of the IMO (International Council on Clean Transportation (ICCT) 2018)

Term	Year	Target	Strategy	Status
Short	2018–2023	New vessels	New EEDI phases	−10% in 2015 −20% in 2020 −30% in 2030
Short	2018–2023	In-service vessels	Operational efficiency measures	SEEMP planning required
Short	2018–2023	In-service vessels	Improvement of existing fleet program	–
Short	2018–2023	In-service vessels	Speed reduction	–
Short	2018–2023	Engine and fugitive emission	Measures to address volatile organic compound and methane emissions	–
Mid	2023–2030	Fuels/new and in-service vessels	Alternative fuel implementation program	–
Mid	2023–2030	In service vessels	Further operational efficiency measures	SEEMP planning required
Mid	2023–2030	In service vessels/fuels	Market-based measures	–
Long	2030+	Fuels/new and in-service vessels	Zero carbon	–

IMO DCS is the latest regulation to mitigate CO_2 emissions worldwide. This regulation is amendments to MARPOL Annex VI by the resolution MEPC.278(70) which has been effective on and after March 1, 2018 (International Maritime Organization (IMO) 2020a). It is a similar regulation to MRV Regulation. The only difference is the IMO DCS covers all ports worldwide while MRV Regulation covers EU and EFTA ports. The first reporting period was started on January 1, 2019 (Gl 2020). Also, the IMO DCS requires an update to the existing SEEMP as the SEEMP Part II. The additional part contains data collection and reporting methods for the specific ship.

In April 2018, at the MEPC 72 meeting IMO has a greenhouse gas (GHG) strategy that aims to lessen CO_2 emissions per transport work at least 40% by 2030 and 70% by 2050 compared to 2008 levels (International Council on Clean Transportation (ICCT) 2018). IMO announced its short-, mid-, and long-term strategies (Table 4.2) to achieve success at their GHG strategy.

4.2.2 Nitrogen Oxide Emission Rules and Regulations

In 2000 at the MEPC.58 meeting, the MARPOL Annex VI was revised and the NO_X Technical Code was adopted (International Maritime Organization (IMO) 2017) and

Table 4.3 NO_X tier limits (International Maritime Organization (IMO) 2020b)

Tier	Ship construction date	Total weighted cycle emission limit (g/kWh) n = engine's rated speed (rpm)		
		$n < 130$	$n = 130–1999$	$n \geq 2000$
I	January 1, 2000	17.0	$45n^{(-0.2)}$	9.8
II	January 1, 2011	14.4	$44n^{(-0.23)}$	7.7
III	January 1, 2016	3.4	$9n^{(-0.2)}$	2.0

entered into force on October 10, 2008 (International Maritime Organization (IMO) 2008). The NO_X Technical Code, Regulation 13, of MARPOL Annex VI aims to limit the shipboard NO_X emissions. The ships which have the engine power above 130 kW are regulated by the code. The code determines the minimum standards for the manufacturing and usage of the code-compliant marine engines and certification of the engines on ships. The NO_X emission limits vary depending on the engine speed and emission tiers (International Maritime Organization (IMO) 2020b). Also, tier limits are different for outside the ECAs and inside ECAs. The NO_X limits can be shown in Table 4.3.

4.2.3 Sulfur Oxide and Particulate Matter Emission Rules and Regulations

The SO_X emissions are regulated by Regulation 14 of MARPOL Annex VI that entered into force in 2005 (International Maritime Organization (IMO) 2020c). This regulation limits the fuel sulfur content by mass (m/m) to mitigate the SO_X emissions from ships. The PM emissions are related to the fuel sulfur content; as a result, the PM emissions are also regulated. The sulfur limits are different for inside ECAs and outside ECAs. Table 4.4 shows the SO_X and PM emission limits.

On January 1, 2020, The IMO Sulfur Cap entered into force. The sulfur limit is 0.50% m/m at the non-ECAs and 0.10% m/m inside the ECAs for the used fuel. Also, it is forbidden to carry fuel that has higher sulfur content than the limits. Around

Table 4.4 SO_X and PM limits (International Maritime Organization (IMO) 2020c)

SO_X and PM limits outside ECAs	SO_X and PM limits inside ECAs
4.50% m/m prior to January 1, 2012	1.50% m/m prior to July 1, 2010
3.50% m/m on and after January 1, 2012	1.00% m/m on and after July 1, 2010
0.50% m/m on and after January 1, 2020	0.10% m/m on and after January 1, 2015

70,000 ships are affected worldwide by these new sulfur limits (Chryssakis et al. 2017).

4.3 Emission Mitigation Technologies and Methods for Ships

The international emission rules and regulations at the maritime transportation have been stricter day by day, and measures have to be taken to comply with the recent regulations to do international maritime trade. There are various ways to mitigate the different types of emissions from ships. This section discusses emission mitigation technologies and methods on ships.

4.3.1 CO_2 Emission Mitigation

CO_2 emissions are related to fuel consumption. The efficient fuel combustion or increasing the efficiency of the systems and operations on a ship is the key element for reduced CO_2 emissions. The design measures, engine and engine room machinery modifications, operational measures, and new technologies are the main classification of the technologies and methods to reduce the CO_2 emission. Table 4.5 shows the CO_2 mitigation technologies and methods for ships.

4.3.1.1 Design Measures

The design measures consist of ship size, ship weight reduction, optimum ship dimensions, improved aft-body, aerodynamic superstructure design, hydrodynamic bulb and bow design, improved propeller design, optimization of propeller, rudder and hull interaction, pre- and post-swirl devices, and contra-rotating propellers.

The energy efficiency for ships is calculated as the CO_2 emission amount per tone-nautical mile. The ship size affects energy efficiency and CO_2 emissions. Larger ships are more efficient and emitting less CO_2 emissions since they can transport more cargo at the same speed and distance than the smaller ships. It was stated that 4–5% higher transport efficiency can be provided by a 10% larger ship (Lassesson and Andersson 2009). Ship weight reduction is also an important measure. The loading capacity will increase if the low-weighted materials are used on a ship and it will affect the energy efficiency and CO_2 emissions of a ship. The optimum ship dimensions with a high length/breadth ratio reduce the resistance and increase the hull efficiency and decrease the CO_2 emissions.

The air resistance of the superstructure reduces energy efficiency and increases CO_2 emissions. An aerodynamic superstructure design improves energy efficiency

Table 4.5 CO_2 mitigation technologies and methods for ships (Lassesson and Andersson 2009; Maritime Knowledge Center (MKC) 2017; Winkel et al. 2015)

CO_2 mitigation technologies and methods			
Design measures	Engine and engine room machinery modifications	Operational measures	New technologies
Ship size	Common rail	Speed reduction	Air lubrication
Ship weight	Engine derating	Voyage optimization	Diesel-electric propulsion
Ship dimensions	Fans, pumps, and compressors	Weather routing	Hybrid auxiliary power generation
Aft-body	Waste heat recovery system	Hull coating and cleaning	Renewable energy
Superstructure		Propeller polishing	Carbon capture system
Bulb and bow		Machinery maintenance	Alternative fuels
Propeller design		Trim and ballast optimization	
Optimization of propeller, rudder, and hull interaction		Shore connection	
Pre- and post-swirl devices			
Contra-rotating propellers			

by the lower air resistance. The improved aft-body and hydrodynamic bulb and bow design reduce the hull–water resistance and again increase the energy efficiency.

The improved propeller design, optimization of propeller, rudder and hull interaction, pre- and post-swirl devices, and contra-rotating propellers aim to improve the water flow to the propeller, reduce the rotational losses from the propeller, and increase the propeller efficiency.

4.3.1.2 Engine and Engine Room Machinery Modifications

Common rail system, engine derating, optimization of the fans, pumps, compressors, and waste heat recovery system (WHRS) are the CO_2 mitigation measures at the engine room of a ship.

The common rail system is an electronically controlled fuel injection system that arranges the fuel injection timing, pressure, and duration independently from the position of the piston (Winkel et al. 2015). This system can determine the optimum fuel injection timing, fuel pressure, and fuel injection duration depending on the engine load. It provides more efficient combustion of the fuel which results in lower CO_2 emissions.

The engine derating is an engine modification that limits the maximum engine power and changes the continuous load of the engine. The combustion parameters are also changed according to the new load range. The engine derating is a speed reduction technique. It provides more optimum and efficient working of the ship main engine at slower speeds of a ship. Lower ship speed results with lower fuel consumption at the total voyage distance and lower CO_2 emissions.

In addition to the main engine modifications, engine room machinery can be optimized for energy-efficient operation. Fans, pumps, and compressors are important elements of an engine room with high electricity consumption. Instead of running at full load all the time, if they changed with variable speed ones, they will work according to the instantaneous need. A study showed that there is a high amount of wasted energy from the seawater pump working at full load (Durmusoglu et al. 2015). This energy is not wasted if the pump is changed with the variable speed pump.

The WHRS is the system that recovers some of the thermal energy from the wasted energy in the exhaust gases. The recovered thermal energy can be used for the electric generation at the turbogenerators, additional mechanical energy to the ship main engine or heating, and freshwater generation on a ship. The WHRS can provide energy saving up to 15% of the engine power (Lassesson and Andersson 2009).

4.3.1.3 Operational Measures

The operational measures are the easiest methods to reduce the CO_2 emissions which can be done by the ship crew and ship management companies. These measures are speed reduction, voyage optimization, weather routing, hull coating and cleaning, propeller polishing, trim and ballast optimization, and shore connection at ports.

The speed reduction (slow steaming) is an effective way to reduce total fuel consumption at a distance. Lower fuel consumption means lesser CO_2 emissions emitted to the atmosphere. It is stated that one knot of speed reduction equals to 11% fuel consumption at the same distance (Lassesson and Andersson 2009). Another report indicated that 10% of speed reduction reduces 20% of fuel consumption and emissions and 30% of speed reduction decreases more than 50% of fuel consumption and harmful emissions (Maritime Knowledge Center (MKC) 2017).

Voyage optimization and weather routing are other operational measures concerning ship navigation. Optimum planning of the voyage including reducing waiting times at ports, or before strait and canal passages is important for the decrease at the fuel consumption. Weather routing is finding optimal routes according to the weather condition. Winds, waves, and currents affect the fuel consumption of a ship; thus, the weather routing can be used as an operational measure for CO_2 reduction.

Maintenance operations on a ship can provide lower fuel consumption and higher ship efficiency. Hull coating and cleaning and propeller polishing are the maintenance operations directly related to fuel consumption. Roughness and biofouling on the hull and propeller increase the resistance that results in higher fuel consumption and CO_2 emissions. A study indicates that periodic hull cleaning leads to 9% of fuel-saving, while dry-docking leads to 17% of fuel-saving (Adland et al. 2018). Machinery maintenance, cleaning, and replacement of parts with the new ones at the scheduled intervals can provide 5–10% lesser fuel consumption and CO_2 emission (Wireman 2011).

Another operational measure is trim and ballast optimization on ships which is a mandatory part in SEEMP. The trim is the difference between the height of the bow and the stern of a ship when it is measured from the waterline. The optimum trim is essential for the reduced resistance at the hull. An optimum trim can provide a 1–5% energy reduction on a ship (Lassesson and Andersson 2009). The optimum ballast is also an important issue on a ship. The ballast water is an extra weight on a ship, and the ballast water uptake has to be arranged according to the optimum trim condition.

The shore connection known as cold-ironing is a shore-based operational measure. The electricity requirement of a ship is taken from the shore by a special cable. Since the diesel generator does not work on a ship, this results with zero fuel consumption and zero CO_2 emission from the ship. On the other hand, the shore electricity should be produced from renewable sources to assume that the operation results with zero CO_2 emission.

4.3.1.4 New Technologies

The new technologies are not common, but it is in the increasing trend in maritime transportation in recent years. The new technologies which are mentioned in this chapter are air lubrication system, diesel-electric machinery, hybrid auxiliary power generation, renewable energy, carbon capture systems (CCS), and alternative fuels. Alternative fuels will be mentioned later.

The air lubrication system is designed to reduce friction between hull and water. It is a system that air is delivered via pumps to out of the hull. The air bubbles are delivered between the hull and water due to the lower resistance between hull–air–water than the hull–water (Lassesson and Andersson 2009). The total efficiency saved is 9% with the air lubrication system (Winkel et al. 2015).

Diesel-electric propulsion is a propulsion system consisting of electric motors powered by diesel engines. The electric motors are connected to the propellers. The diesel-electric propulsors are able to work at higher total efficiency than the conventional propulsion type because it can respond quicker at load changes, especially at maneuvering operation of a ship. The maneuvering operation is the navigation of a ship near coastal areas, such as port entry, canal, or strait passages. Another new technology is the hybrid auxiliary power generation on a ship by using fuel cells and batteries. The hydrogen, methanol, or natural gas fuel cells can be used to generate energy that is supportive of the main engine. Since the maximum theoretical efficiency is higher for fuel cells, it increases the energy efficiency of a ship and reduces the CO_2 emissions (Lassesson and Andersson 2009).

Nowadays, renewable energy such as wind and solar power is used on ships. Soft sails, rigid wing sails, kites, and Flettner rotors are some of the equipment and systems for getting wind energy as an auxiliary energy to the ship main engine. Also, solar panels are placed on the deck of the ship to change solar energy to the electricity by storing at the batteries. These systems reduce fossil fuel consumption of a ship and increase the use of zero-carbon energy.

Carbon capture systems (CCSs) are mostly used in power plants, steel, and cement industries, but there are some studies to apply CCS on ships (Zhou and Wang 2014; Akker 2017; Feenstra et al. 2019). Basically, a CCS captures the CO_2 emission from the ship funnel as an after-treatment system. The CO_2 capture rate varies from 80 to 95% depending on the system specifications (American Society of Civil Engineers (ASCE) 2014). It does not measure to reduce the CO_2 emission, but a measure to capture and store onboard.

4.3.2 NO_X Emission Mitigation

NO_X emission consists of NO and NO_2 emissions. Although there are two types of emissions in NO_X, NO has a higher proportion than NO_2; therefore, NO kinetics are dominant at NO_X formation. The NO_X formation highly depends on maximum in-cylinder temperature and oxygen content and also related to the pressure rise rate (PRR) and maximum in-cylinder pressure since high PRR and maximum in-cylinder pressure result in sudden high in-cylinder temperature. There are various mitigation technologies and methods to overcome NO_X formation at marine diesel engines. Pre-combustion techniques, combustion intervention techniques, and after-treatment technologies which are shown in Table 4.6 can be used on a marine diesel engine. Alternative fuels will be discussed further in detail.

Pre-combustion techniques for NO_X reduction are water/steam injection to the intake air, fuel–water emulsion, engine modification, and alternative fuel usage. The marine diesel engine manufacturer, MAN B&W, has a system named "Scavenge Air Moisturizing System (SAMS)" which injects seawater into the intake air of an

Table 4.6 NO_X mitigation methods for ships

Pre-combustion	Combustion intervention	After-treatment
Water/steam injection to the intake air	Exhaust gas recirculation system	Selective catalytic reduction system
Fuel–water emulsion	Water/steam injection into the cylinder	
Engine modification		
Alternative fuels		

engine. The purpose is to reduce local maximum combustion temperature in the combustion chamber by the cooling effect of the water (MAN 2014). The lower maximum combustion temperature limits the NO_X formation. Also, steam can be introduced to the intake air to do the same effect as water vapor. This method decreases engine efficiency and increases the specific fuel consumption (SFC) and PM emission (Andreoni et al. 2008). The water/steam injection can be also used as a combustion intervention technique. The water/steam is injected during the combustion process as the combustion intervention to do the same effect as the pre-combustion technique.

Fuel–water emulsion is the homogenous fuel–water mixture is used as a fuel at marine diesel engines. It has a similar effect to the SAMS. Reduction at the maximum combustion temperature is provided that results in lower NO_X emission with slightly increased SFC. The study results show that 30% NO_X reduction was provided with 20–80% water–fuel emulsion (Kim et al. 2018) at a four-stroke diesel engine. MAN states that 10% NO_X reduction was achieved for each 10% water added at their two-stroke marine diesel engine (MAN 2014).

The engine modification is the NO_X mitigation method at pre-combustion and combustion intervention stages. Optimum engine modification can achieve to lower NO_X emission. Optimized fuel injection valves and nozzles, the number and size of the spray holes, fuel injection retardation, compression ratio reduction, increase of injection pressure, induction swirl optimization, and intake air system modification are some of the engine modifications (MAN 2014; Andreoni et al. 2008).

Exhaust gas recirculation (EGR) system is a combustion intervention technology. It recirculates some of the exhaust gases, after cools down and cleans, delivers into the cylinder to reduce the oxygen content in the cylinder, and decreases the nitrogen oxidation inside the cylinder (Zincir 2019). NO_X reduction of up to 70% can be achieved with EGR (MAN 2014). The system decreases engine efficiency and NO_X emissions while increasing SFC, CO_2, and PM emissions (Zincir 2014).

The selective catalytic reduction (SCR) system is an after-treatment system that uses ammonia or urea to mitigate NO_X emission by the chemical reaction. It can remove 90–95% of NO_X emission (MAN 2014). The system has side effects on the engine such as reduced engine efficiency, increased SFC, and CO_2 emissions (Zincir 2019).

4.3.3 SO_X Emission Mitigation

The SO_X emission depends on fuel sulfur content. Using low-sulfur heavy fuel oil or marine diesel oil is an option to reduce SO_X emission. The sulfur scrubber as an after-treatment technology is another way to decrease the SO_X emission from ships. There are wet-type scrubbers that use either seawater or freshwater with a caustic soda (NaOH) solution, and dry-type scrubbers use chemicals and capture SO_X and PM emissions inside the scrubber (Zincir 2014). Local regulations of California waters do not allow to use the scrubbers and force ship operators to use low-sulfur fuels. The sulfur scrubbers reduce engine efficiency and increase SFC and CO_2 emission.

The last way to mitigate SO_X emission is the usage of sulfur-free alternative fuels on ships (Andersson and Salazar 2015).

4.3.4 Mitigation Method for All Regulated Emissions: Alternative Fuels

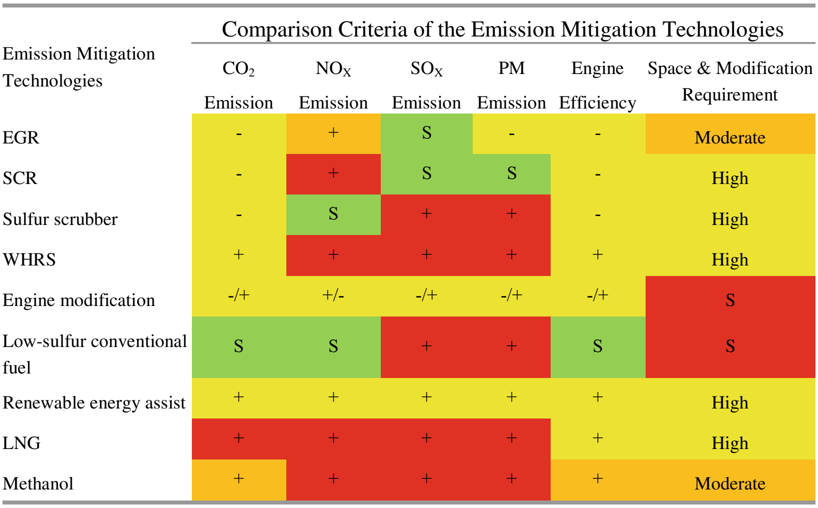
Up to now, emission mitigation methods and technologies for various emission types were explained. It can be understood that an emission mitigation method or technology only decreases only one type of emission and it does not have any effect on other types of regulated emissions. Therefore, sometimes two types of technology, i.e., SCR for NO_X emission and sulfur scrubber for SO_X and PM emissions, are applied to a ship to comply with recent emission rules and regulations. It means high investment costs and enough space requirements on a ship. To overcome this issue, alternative fuels can be used as fuel. Using alternative fuels can reduce the different types of emissions at once without applying additional equipment for each emission target.

The alternative fuels for the maritime transportation are liquefied natural gas (LNG), methanol, liquefied petroleum gas (LPG), ethanol, ethane, dimethyl ether (DME), biodiesel, biogas, synthetic fuels, ammonia, and hydrogen (Chryssakis et al. 2014; Sverrisdottir 2018; Zincir and Deniz 2018; Bakhtov 2019). And the possible ones for the future are straight vegetable oil (SVO), bio-ethanol, and bio-ammonia (Maritime Knowledge Center (MKC) 2017). Although there is a large variety of alternative fuels for the maritime transportation, the most promising alternatives are LNG and methanol, due to their good supply infrastructure and biofuel counterparts as biomethane and biomethanol (Moirangthem 2016). Recent alternative fueled ship numbers are 169 LNG-fueled ship in operation and 216 ships in order, 10 methanol-fueled ship in operation and 6 in order, 12 LPG-fueled ships in operation and 14 ships in order, and 2 ethane fueled ships in operation and 2 in order (Zincir and Deniz 2018; DNV GL 2020).

LNG, LPG, and methanol can decrease NO_X emission by up to 90%, below the NO_X Tier III Limit. The CO_2 emission reduction is 23%, 20%, and 10% by using LNG, LPG, and methanol, respectively, and the sulfur-free structure of these fuels results with a 90–97% reduction at SO_X emission and 90% PM emission (ClassNK 2018). However, alternative fuels can increase engine efficiency and decrease SFC in contrary to the after-treatment technologies.

Table 4.7 compares the emission mitigation technologies with the regular marine diesel engine without any emission mitigation technology as the baseline. The most popular technologies and alternative fuels at maritime transportation are included in the comparison table. The emission types, engine efficiency, and space and modification requirement on a ship for the technology are the criteria. Yellow, orange, red, and green colors indicate low effect, moderate effect, high effect, and no effect, respectively. At space and modification requirement criterion, colors have reverse meaning.

Table 4.7 Comparison of the emission mitigation technologies and alternative fuels



Emission Mitigation Technologies	Comparison Criteria of the Emission Mitigation Technologies					
	CO_2 Emission	NO_X Emission	SO_X Emission	PM Emission	Engine Efficiency	Space & Modification Requirement
EGR	-	+	S	-	-	Moderate
SCR	-	+	S	S	-	High
Sulfur scrubber	-	S	+	+	-	High
WHRS	+	+	+	+	+	High
Engine modification	-/+	+/-	-/+	-/+	-/+	S
Low-sulfur conventional fuel	S	S	+	+	S	S
Renewable energy assist	+	+	+	+	+	High
LNG	+	+	+	+	+	High
Methanol	+	+	+	+	+	Moderate

(− = worse than the baseline, + = better than the baseline, S = the same as the baseline)

Yellow, orange, and red colors indicate high requirements, moderate requirements, and low requirements, respectively.

EGR as a NO_X emission mitigation technology has a medium reduction effect (70% of reduction) and slightly higher SFC, CO_2, and PM emissions, and slightly lower engine efficiency with no effect on SO_X emission. EGR has moderate space and modification requirements on a ship when it is compared with other technologies, such as SCR and sulfur scrubber. Increased CO_2 and PM emissions and reduced engine efficiency are the negative sides of the EGR.

SCR is another NO_X emission mitigation technology that has a high reduction effect (90–95% of reduction). It slightly increases CO_2 emission and decreases the engine efficiency, and there is no effect on SO_X and PM emissions. SCR has a high space and modification requirement on a ship since it has a complex system with equipment high in number. The CO_2 emission increase, engine efficiency reduction, and high space and modification requirement for the system elements are the disadvantages of SCR.

The sulfur scrubber highly reduces SO_X and PM emissions, slightly increases CO_2 emission, and reduces engine efficiency with no effect on NO_X emission. It has a high space and modification requirement on a ship the same as SCR. The disadvantages of the sulfur scrubber are slightly increased CO_2 emission, reduced engine efficiency, and high space and modification requirement of the system.

WHRS can reduce total fuel consumption onboard by getting energy from the wasted exhaust energy and use it at a steam generation that can be used at a turbogenerator for ship electricity production, additional mechanical energy to the ship main engine, heating, freshwater generation, etc. This results in slightly lower CO_2,

NO_X, SO_X, and PM emissions with slightly higher engine efficiency. The WHRS also needs high space and modification requirements on a ship.

The engine modification can affect the emission formation. The NO_X emission can be reduced with the trade-off of slightly higher SFC, CO_2, SO_X, and PM emissions and slightly lower engine efficiency by changing fuel injection timing or injection pressure. On the other hand, vice versa can be happened by doing engine modification on the main engine. There is no need for space and modification requirements on a ship.

Use of low-sulfur conventional fuel highly decreases the SO_X and PM emissions, but there is no effect on CO_2 and NO_X emissions, and engine efficiency. Also, there is no need for space and modification requirements on a ship since the same fuel system is used.

The renewable energies, wind and solar, assist to the main engine or auxiliary engines. This reduces total fuel consumption on a ship that results in slightly lower CO_2, NO_X, SO_X, and PM emissions with slightly higher engine efficiency. Renewable energy systems require high space and modification on a ship, and it is the disadvantage of these systems.

LNG is the most popular alternative fuel in maritime transportation. When it is compared with the conventional-fueled main engine, the use of LNG on a ship results in extremely lower CO_2, NO_X, SO_X, and PM emissions with slightly higher engine efficiency. The LNG storage and fuel system have a high space and modification requirements on a ship. It requires special LNG tanks for the storage, double-walled fuel piping with the LNG supply system to the main engine. The main engine must have a modified fuel injection system with the safety systems for LNG fuel. High space and modification requirement is the disadvantage of LNG fuel.

Methanol is the second most popular alternative fuel in maritime transportation nowadays. Methanol moderately reduces CO_2 emissions and highly decreases NO_X, SO_X, and PM emissions. Methanol fuel usage moderately increases engine efficiency if the optimum combustion conditions are provided. Methanol storage and fuel system require some space and modification on a ship, but they are less than LNG storage and fuel system. There is no need for special storage tanks; methanol can be stored in conventional fuel tanks after minor modifications. Similar fuel supply and safety equipment with LNG are needed for methanol.

The moderate space and modification requirement on a ship and moderate increase at the engine efficiency is the advantage of methanol on LNG. Methanol with biofuel option has more advantages since it is carbon–neutral fuel. Also, there are other production methods by using renewable electricity and carbon capture from the atmosphere or waste CO_2 which is called electrofuel (Verhelst et al. 2019).

4.4 Methanol at Maritime Transportation

Methanol is one of the promising alternative fuels at the maritime transportation and maritime projects, and commercial applications are in increasing trend. This section gives recent information about maritime rules and regulations for methanol as a fuel for ships, marine projects, and commercial applications of methanol on ships.

4.4.1 Maritime Rules and Regulations for Methanol as a Fuel for Ships

IMO has prepared and implemented maritime rules and regulations for the ships doing worldwide trade. It has also had studies about rules for the usage of alternative fuels on ships. The International Code of Safety for Ships Using Gases or Other Low-Flashpoint Fuels (IGF Code) has been effective since January 2017. The IGF Code aims to determine an international minimum standard for ships using gas fuels or low-flashpoint liquids as a fuel. The Code contains mandatory criteria for the design and installation of machinery, equipment, and systems for ships using gases or other low-flashpoint fuels (IMO Web Site 2020). Firstly, the Code has concentrated on LNG, but the draft guidelines for the safety of ships using methyl/ethyl alcohol as fuel were prepared and sent to the Maritime Safety Committee for approval since these fuels are low-flashpoint fuels (IMO Web Site 2020).

In addition to the IMO rules, there are rules and guidelines of classification societies to standardize international maritime transportation. The classification societies do classification and statutory services of ships and help IMO about maritime safety and pollution prevention. They develop and apply their own rules, in addition to the IMO rules, and verify that the ships comply with the international and/or national regulations (International Association of Classification Societies (IACS) 2020). The classification societies determine their minimum standards which are usually higher than the IMO standards and check the structural hull strength, propulsion and steering systems, power generation, other auxiliary machinery systems, and ship safety systems. The classification societies have their own guidelines for methanol-fueled ships. The International Association of Classification Societies (IACS) members, DNV GL, and Lloyd's Register apply their own rules when they do the classification of these ships. DNV GL gives approval to the methanol-fueled ships by the certificate with the notation of LFL fueled (DNV GL 2014) and Lloyd's Register with the notation of LFPF (GF, ML) (Lloyd's Register 2019).

4.4.2 Marine Methanol Projects and Commercial Applications

Various methanol projects at the maritime industry have been done until now. The project subjects change from different combustion concepts to risk assessment of the use of methanol on ships. Besides, there are commercial applications now doing maritime trade. The section starts with the marine methanol projects.

METHAPU (2006–2010)

METHAPU was an EU project with 6 project partners. The project aimed to assess the maturity of methanol technology on a commercial vessel, validation of methanol solid oxide fuel cell (SOFC) technology, determination of the technical requirements of the use of methanol on commercial vessels, assessment of short-term and long-term environmental impacts, and determination of the future research pathways for methanol SOFC for larger ships (European Commission 2020).

EffShip (2009–2013)

EffShip was the Swedish-based project. The aim of the EffShip was to find the best solution to comply with SO_X and NO_X limits in the short-term and GHG reduction targets in the medium term and long term (Andersson and Salazar 2015). Various technologies and marine fuels were evaluated. Methanol was found as the best alternative fuel with its advantages of availability, existing infrastructure, price, easy application to a ship, and maturity of the system (Fagerlund and Ramne 2013).

e4ships and Pa-X-ell (2009–2016)

The e4ships project was funded by the German government. The aim of the project was to develop the most advanced and largest methanol fuel cell. The Pa-X-ell project was the subproject of e4ships. It focused on the application of the methanol fuel cell on a ferry named Mariella (Maritime Knowledge Center (MKC) 2018).

CleanShip (2010–2013)

CleanShip focused on clean shipping in the Baltic Sea. The ports in the Baltic Sea and the shipowners whose ships were operating in the Baltic Sea involved in the project. Methanol was considered as a possible alternative fuel for clean shipping in the Baltic Sea. Also, a methanol fuel cell as an auxiliary engine was tested in the project (Andersson and Salazar 2015; Paulauskas and Lukauskas 2013).

SPIRETH (2011–2014)

SPIRETH had commenced between 2011 and 2014. The aim of the project was to observe the laboratory test results of methanol and dimethyl ether (DME) from methanol use on a marine diesel engine (Andersson and Salazar 2015). In addition to this, the project contributed to the IMO's draft IGF Code by the risk and safety analysis in the project. The findings showed that methanol is a promising alternative fuel for the Nordic region and the Baltic Sea (Maritime Knowledge Center (MKC) 2018).

PILOT Methanol (2014–2015)

The PILOT Methanol project is a ship conversion and operation of the Ro-Pax ferry Stena Germanica. The ship was converted to the dual-fuel operation with methanol and diesel. Stena Germanica was the first methanol-fueled ship. The methanol fuel conversion requirements and procedures on a ship were determined, and a bunkering facility was formed. Besides, this project assisted in the regulation development for the methanol fuel operation both on a ship and during bunkering (Andersson and Salazar 2015). The ship conversion was completed in April 2015, and she has operated since that date.

SUMMETH (2015–2017)

The SUMMETH project aimed to test and evaluate different methanol combustion concepts, including spark-ignition (SI) and compression ignition (CI) concepts, for the smaller engines (between 250 and 1200 kW), to investigate the total GHG reduction potential of methanol as a marine fuel, determine the conversion requirements for a ship, and assess the requirements for transport, distribution, and sustainable production of methanol for the maritime industry (SUMMETH 2020). The project partners were Lund University, Farjerederiet Trafikverket, Marine Benchmark, ScandiNAOS, Scania, Svenskt Marintekniskt Forum, SSPA, VTT, and the project was financed by Swedish Maritime Administration, Methanol Institute, Vastra Götalandsregionen, and Oiltanking.

MethaShip (2015–2017)

The project partners Meyer Werft, Lloyd's Register, and Flensburger Schiffbau-Gesellschaft involved in the MethaShip funded by the German government. The aim of the project was the assessment of the feasibility of new-building methanol-fueled ships. There were two cruise ships and Ro-Pax ferry designs developed as the project output (Andersson and Salazar 2015).

LeanShips (2015–2019)

LeanShips was an EU Horizon 2020 project with 49 partners. This project had different work packages, and one of them was "The potential of methanol as an alternative fuel." In this work package, a high-speed marine diesel engine had been modified to operate with the methanol–diesel dual-fuel engine concept. The laboratory tests were focused on engine efficiency and emissions. The methanol–diesel dual-fuel operation had an improvement of 12% in brake thermal efficiency, and NO and soot emissions averagely reduced by 60 and 77% at all load range, respectively (LeanShips Project website 2020).

GreenPilot (2016–2018)

The GreenPilot project comprised Svenskt Marintekniskt Forum, SSPA, ScandiNAOS, the Swedish Transport Administration, and the Swedish Maritime Administration. The project focused on the conversion of small boats to the methanol-fueled boats and engine efficiency and emissions of the converted boat. The conversion requirements were determined, and various methanol combustion concepts were evaluated in the project (Maritime Knowledge Center (MKC) 2018).

The research and development projects in the maritime industry have increased the maturity of methanol fuel in maritime transportation. There are 10 methanol-fueled ships in operation and 6 in order recently. The first methanol-fueled ship is Stena Germanica that has operated since April 2015. Its operation resulted in 3–5 g/kWh NO_X emission, below 1 g/kWh CO and THC emissions, low PM emission from pilot MGO, and 99% SO_X reduction with higher engine efficiency (Stefenson 2016). Waterfront Shipping ordered three methanol dual-fuel chemical tankers and they started to operate them in April 2016 (Maritime Knowledge Center (MKC) 2018). These ships were the first new-building methanol-fueled ships in history. The ships can operate with methanol, fuel oil, marine diesel oil, or gas oil. After these pioneers, the methanol-fueled ship fleet has been in increasing trend.

4.5 Methanol Properties and Combustion Concepts

This section approaches methanol properties from the aspect of maritime transportation and explains the important fuel properties on ships. Besides, possible methanol combustion concepts for marine diesel engines are mentioned and compared.

4.5.1 Methanol Properties from the Aspect of Maritime Transportation

Methanol has been one of the top five produced chemicals worldwide (Independent Commodity Intelligence Services (ICIS) 2017), with an annual production capacity of about 95 million tons (Nash 2015) that includes the production of 20 million tons as a fuel or fuel blend (Landälv 2017). Methanol can be produced from fossil fuel sources, mostly from natural gas and coal, or renewable sources. It can also be produced from any carbonaceous sources including wood, agricultural, and municipal waste (Yao et al. 2017). This type of methanol is biomethanol. It is stated that biomethanol can reduce GHG emissions significantly compared to methanol from fossil fuels (Maritime Knowledge Center (MKC) 2018). Additionally, there is methanol that is produced by using renewable electricity, and carbon capture from the atmosphere or waste CO_2 is called electrofuel (Verhelst et al. 2019). Methanol from renewable sources is a way for sustainable maritime transportation with 100% renewable fuels (Andersson and Salazar 2015).

Methanol has been considered as a fuel option since the 1970s, and it was used as a motor fuel until the mid-1990s. Methanol constitutes a 7–8% transportation fuel pool of China, and up to 3% of methanol blend to gasoline is permitted in European countries (Aakko-Saksa et al. 2020). Nowadays, methanol is also one of the promising alternative fuels to conventional ones in maritime transportation. Table 4.8 shows methanol properties.

Emissions

Methanol has the chemical formula of CH_3OH. It has a high H/C ratio, and it does not form particulate matter since methanol is not a long-chain hydrocarbon (Verhelst et al. 2019). If molar mass and lower heating value (LHV) of methanol are considered,

Table 4.8 Properties of methanol (Verhelst et al. 2019)

Specifications	Methanol
Chemical formula	CH_3OH
RON	107–109
MON	92
H/C	4
O/C	1
LHV (MJ/kg)	19.9
A/F_S	6.45
Density (kg/m^3)	790
Vapor density (kg/m^3)	1.42
Boiling point at 1 bar (°C)	65
Heat of vaporization (kJ/kg)	1100
Dynamic viscosity (20 °C) (mPas)	0.57
Molecular weight (kg/kmol)	32.04
Oxygen content by mass %	49.93
Hydrogen content by mass %	12.58
Carbon content by mass %	37.48
Auto-ignition temperature (°C)	465
Flashpoint (°C)	12
Adiabatic flame temperature (°C)	1870

methanol emits 20% less CO_2 emission while its combustion when compared with diesel with similar engine efficiencies (Maritime Knowledge Center (MKC) 2018). Another report states that methanol combustion in an internal combustion engine results in an approximately 10% reduction at CO_2 emission compared with heavy fuel oil (HFO) or distillate fuel (Gl 2019). The oxygen atom in the methanol molecule promotes more efficient combustion with lesser air requirement that lowers CO_2 and PM emissions. Alcohol fuel, methanol, decreases soot emissions by the assist of the oxygen atom. Methanol combustion has reduced combustion temperature that offers lesser NO_X formation down to IMO Tier III Limit (Andersson and Salazar 2015). Using methanol in diesel engines is a promising way to reduce both soot and NO_X emissions together (Tuner 2015). The sulfur-free structure of methanol results in no SO_X emission from the methanol combustion, and a ship can comply with the new IMO sulfur emission cap. In addition to this, methanol combustion on diesel engines can reduce polycyclic aromatic hydrocarbons that are the main reason for diesel fuel toxicity (Wuebben 2016).

Efficiency

Liquid fuels absorb heat energy from inside of the cylinder after the injection during the evaporation event. This is called the heat of vaporization (kJ/kg). Methanol has almost 4 times higher heat of vaporization than the diesel fuel (Maritime Knowledge

Center (MKC) 2018). It means methanol absorbs more heat energy to vaporize and it results in a charge cooling effect and a lower in-cylinder temperature. Methanol combustion has a lower heat transfer loss, lower compression work, and higher engine efficiency related to the charge cooling effect (Shamun et al. 2018; Zincir et al. 2019a). Also, it raises the intake air density and volumetric efficiency of the engine (Verhelst et al. 2019). According to the MIT researchers, a diesel engine can be downsized from a 9-L engine to a 5.5-L engine and 30% more engine power with the use of methanol (Wuebben 2016). Besides, the charge cooling effect of methanol reduces NO_X emission since the combustion temperature is lower than the diesel fuel combustion. The use of methanol at maritime transportation brings more efficient and emission regulation compliant marine diesel engines in operation which will contribute to sustainable maritime transportation.

Unique properties

Methanol has other unique properties. Methanol has a significant molar expansion that increases in-cylinder pressure at the time of the combustion event without additional heat (Tuner 2015). Methanol is a high octane fuel that causes high auto-ignition resistance. On the other hand, the cetane number of methanol is low. Methanol has a higher laminar flame velocity than the conventional fuels that provide faster combustion, lower heat loss to the cylinder walls, and higher engine efficiency. The high octane and low cetane number of methanol make it an unsuitable fuel for compression ignition engines, but it can be burnt by doing hardware changes or/and fuel reforming (Maritime Knowledge Center (MKC) 2018). Methanol has low lubricity due to its lower kinematic viscosity. It has lower kinematic viscosity than diesel, so lubrication additives have to be used with methanol to prevent corrosion at injection pumps, injectors, and other fuel system equipment (Tuner 2015). Methanol is highly corrosive to some materials. The polar structure of methanol brings dry corrosion on the materials (Verhelst et al. 2019). Metals including zinc, copper, lead, aluminum, magnesium and elastomers, plastics, and rubber are extremely affected by methanol (Methanol Institute, Compatibility of metals & alloys in neat methanol service; Methanol Institute, Compatibility of elastomers in neat methanol service).

Safety on a ship

IMO indicates that marine fuels have to have a flashpoint higher than 60 °C on a ship (International Maritime Organization (IMO) 1974). Methanol is one of the low-flashpoint fuels. It has a flashpoint of 12 °C, and additional safety precautions have to be taken on a ship. Similar safety precautions to LNG-fueled ships are applied for the methanol-fueled ships. Besides its low flashpoint, methanol has an invisible flame and quite wide flammability limits between 6.7 and 36%. Although there are some considerations about the methanol safety on a ship, methanol vapor is heavier than air and methanol fire can be extinguished with water (Aakko-Saksa et al. 2020). High auto-ignition temperature reduces the risk of self-ignition or explosion of methanol. Other than its low flashpoint, methanol is in liquid at ambient temperature and pressure, and almost similar to HFO, and similar handling and safety practices could be applied (Andersson and Salazar 2015).

Storage and fuel operation on a ship

Methanol has similar physical properties to conventional marine fuels, such as HFO, and it can be stored at the same bunker tanks after minor modifications (Andersson and Salazar 2015; Stocker 2018; Zincir et al. 2019b). This means requirements for methanol storage tanks, equipment, and procedures are lesser than the LNG storage and have reduced capital cost. Additionally, since methanol is infinitely miscible in water, it is not harmful to the environment and can be stored in the double hull bottom of the ship (Verhelst et al. 2019; Landälv 2017). The LHV of methanol is less than half of the LHV of diesel; therefore, roughly twice the tank volume of the conventional fuel storage tank is required for the same distance of navigation. But the double hull bottom storage opportunity of methanol is an advantage for methanol storage on a ship. Lower LHV of methanol also affects the fuel injection capacity. New injectors with a higher fuel flow rate have to be used to provide the same engine power as conventional fuels.

Environmental impact

Methanol can be assumed as environmentally friendly fuel. Fuel spillages from ships are important environmental incidents for marine ecology. Methanol is biodegradable and has a short half-life time (1–6 days) in ground and water (Aakko-Saksa et al. 2020). Methanol dilutes quickly in water and breaks down into CO_2 and water (Landälv 2017). The methanol spillage forms less ecological threat; on the other hand, it can increase sea vegetation (Maritime Knowledge Center (MKC) 2018). Besides, when methanol is compared with LNG, the vapor slip of methanol does not increase the GHG effect.

Impact on health

Methanol is toxic for human beings and causes blindness when it is ingested as 10 mL and is fatal when it is ingested 60–100 mL. Methanol is also dangerous if a person uptakes methanol through the skin and by inhalation (Aakko-Saksa et al. 2020). Methanol is odorless below 2000 ppm in air, so when it is used as a fuel on a ship, the fuel system has to be completely closed-off, the ventilation system has to be placed, and nobody has to touch methanol (Andersson and Salazar 2015). Although it is toxic, it does not have a cancerous effect contrary to diesel.

Methanol is a significant alternative marine fuel which promises good combustion properties, high engine efficiency, low engine emissions, and low environmental impact when its spillage or vapor slip to the atmosphere. Drawbacks of methanol are low LHV, larger storage tanks than the conventional fuels, and toxicity.

4.5.2 Methanol Combustion Concepts on Marine Diesel Engines

The internal combustion engines convert chemical energy of the fuel to mechanical energy by the combustion of fuel as a thermodynamic process. Fuel properties are an important aspect of the combustion event. The properties of methanol and their effects on the combustion event were mentioned in the previous section. Besides the fuel properties, fuel combustion strategy compatibility is also crucial for high engine efficiency and low emission formation. There are three main combustion strategies for internal combustion engines. These are compression ignition (CI), spark ignition (SI), and homogenous charge compression ignition (HCCI). Three main combustion strategies form a combustion strategy triangle, and they are the corner points of the triangle (Johansson 2016). In addition to the main combustion strategies, there are intermediary combustion strategies between three main combustion strategies which are suitable to combust methanol in a diesel engine. The intermediary combustion strategies are dual-fuel combustion, direct injection spark ignition (DISI), reactivity-controlled compression ignition (RCCI), and partially premixed combustion (PPC). Figure 4.1 shows the combustion concepts for methanol. Since the book section focuses on marine diesel engines, the combustion strategies for the marine diesel engines will be discussed.

4.5.2.1 Methanol–Diesel–Additive Emulsion (MD95) Combustion Strategy

Before explaining the intermediary combustion strategies, a methanol-additive emulsion combustion strategy should be mentioned. It is a combustion strategy that can be applied during conventional CI combustion. This strategy uses 95% methanol and 5% diesel with the ignition improver as a fuel emulsion (Ellis et al. 2018). MD95 combustion strategy uses a very high compression ratio (28:1) to burn methanol, and the ignition improver also promotes the combustion. There are studies on Scania heavy-duty

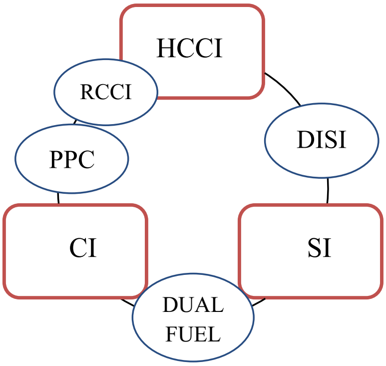


Fig. 4.1 Scheme of the combustion concepts (figure reproduced and adapted) (Zincir 2019; Johansson 2016)

engines with MD95 (Aakko-Saksa et al. 2020; Ellis et al. 2018). This combustion strategy can be used on smaller ships, but the main issue is high compression ratio and material durability in the long-term.

4.5.2.2 PFI-SI Methanol Combustion Strategy

PFI-SI means port fuel injection—spark-ignited combustion strategy. It is a combustion strategy similar to the conventional SI engines, but it can be applied to diesel engines. The diesel engine is modified to run as a SI and PFI engine. Methanol injected into the intake manifold and air–fuel mixture enters into the cylinder. And then, the mixture is ignited by a spark plug. In a study, the NO_X emission complied with the IMO Tier III Limit, and almost zero emission was recorded with similar engine efficiency and torque to a conventional CI (Ellis et al. 2018).

4.5.2.3 HCCI Combustion Strategy

HCCI, homogeneous charge compression ignition, combustion strategy is the third main combustion strategy. It is one of the first low-temperature combustion strategies (Lönn 2019). The HCCI is comparable to the SI engine, the mixture of fuel and air enters into the cylinder, and the combustion event is initiated by the raised pressure and temperature during the compression stroke.

The combustion starts in different areas in the combustion chamber at the same time and can be called a distributed reaction (Johansson 2016). Actually, in contrary to the strategy name, the combustion event is not homogenous; there are fast-burning zones and slow-burning zones in the combustion chamber. The in-cylinder charge is diluted to keep the reactivity speed to prevent high PRR and peak in-cylinder pressure during the combustion event (Zincir 2019). This brings low-temperature combustion that results in high engine efficiency and low soot and NO_X emissions (Tuner 2015). There are disadvantages of the HCCI which are difficulties in the combustion control, low power production range, high PRR, high HC, and CO emissions (Zincir et al. 2019a; Lönn 2019). The disadvantages of the HCCI limit commercial using of this combustion strategy.

4.5.2.4 Dual-Fuel Combustion Strategy

Dual-fuel combustion strategy, one of the intermediary combustion strategies, uses two different fuels that one of them has a higher cetane and lower octane than the other one. The main fuel is methanol as a high octane fuel, and the pilot fuel is diesel as a low octane and high cetane fuel. Methanol can be injected into the port or directly into the cylinder. Diesel is injected into the cylinder on to the methanol–air mixture in the cylinder and ignites the mixture (Tuner 2016). The pilot fuel amount for igniting the methanol–air mixture can be low as 1–2% of the total fuel (Johansson 2016). The timing of the combustion event is determined by the diesel injection timing, and the methanol–air mixture is burned with flame propagation similar to SI engines (Zincir 2019).

Large marine diesel engine applications use this combustion strategy. Two top marine diesel engine manufacturers, MAN and Wartsila, have commercial methanol–diesel dual-fuel marine diesel engine applications on various ships, such as Stena Germanica and several tankers of Waterfront Shipping.

4.5.2.5 RCCI Combustion Strategy

Reactivity-controlled compression ignition (RCCI) combustion strategy comprises two different fuels with different octane numbers in various amounts to provide an optimum combustion event. This combustion strategy is similar to the dual-fuel strategy. High octane fuel is injected into the intake port and is premixed with air while low octane fuel is injected directly into the cylinder. Also, it is similar to the HCCI combustion strategy since the RCCI uses dilution and low-temperature combustion like the HCCI (Tuner 2015). The high engine efficiency, 60%, has been reported (Splitter et al. 2013), and similar emission characteristics to the HCCI combustion strategy have been achieved. Although the RCCI has high engine efficiency, this combustion strategy is impractical due to the two fuel tanks and fuel supply systems to the diesel engine.

4.5.2.6 DISI Combustion Strategy

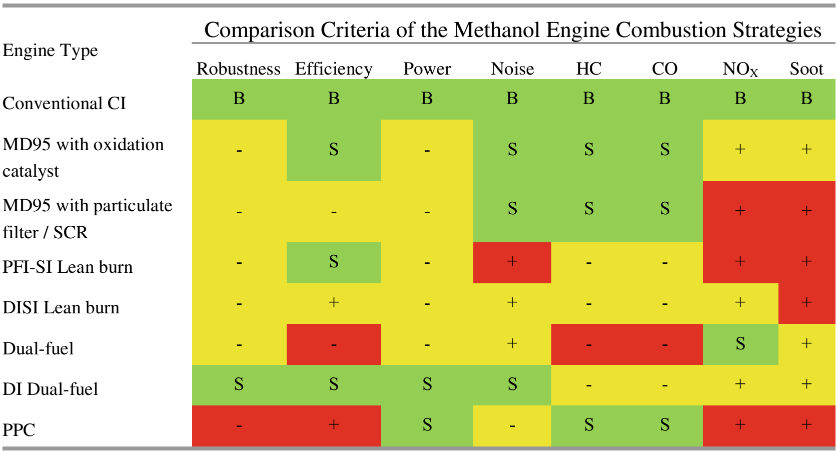
Direct injection spark ignition (DISI) is a combustion strategy between SI and HCCI. Methanol is combusted by a spark plug mounted to the cylinder head of diesel engines. The combustion event started the same as SI engines with flame propagation and ends with similar to the HCCI combustion strategy. The in-cylinder mixture should be suitable for proper flame propagation and also be diluted to slow down the auto-ignition process (Johansson 2016). To heat the in-cylinder mixture, negative valve overlaps are often used to hold residual gases in the cylinder and the spark plug ignited the diluted in-cylinder mixture (Li 2018). The engine efficiency of more than 51% can be achieved with a stratified late injection of methanol in the DISI combustion strategy (Björnestrand 2017). But the operation range is narrow between the knock and misfire during the stratified combustion.

4.5.2.7 PPC Combustion Strategy

Partially premixed combustion (PPC) is a combustion strategy combining conventional CI and HCCI combustion strategies. The main principle of PPC is the separation of the start of combustion and end of injection (Tuner 2016). The aim of a comparatively earlier injection of methanol than the conventional CI during the compression stroke is to constitute a partially homogenous air–fuel mixture in the cylinder before the combustion event. The combustion event starts with a stratified charge, but it is not diffusion-controlled, spray-driven combustion (Johansson 2016). The PPC strategy has simple combustion control, low NO_X and soot emissions, and good engine efficiency (Zincir et al. 2019a, b). Methanol has a high burning rate at the PPC strategy that leads to reduced heat transfer losses and lowers NO_X emission since high-temperature combustion period is lower (Shamun 2019). The PPC strategy achieved engine efficiency which was higher than 53% with methanol as a fuel (Shamun et al. 2017a). The split injection can be used to form an optimum combustion event with high engine efficiency and low engine emissions.

The methanol project named SUMMETH is one of the crucial projects for maritime transportation. Possible combustion strategies for marine diesel engines powered between the ranges of 250 and 1200 kW. The engine power range represents the main engine of small tonnage ships or auxiliary diesel engines for electricity generation on large ships. But this project is the only project that compares methanol combustion strategies for marine diesel engines in detail, so this study can also give an opinion about the marine engines larger than 1200 kW. Table 4.9 shows the compared methanol engine combustion strategies with additional after-treatment methods. There are more combustion strategies in the study (Ellis et al. 2018), but some of them are not included in the table. The alternative combustion strategies are compared with the conventional CI engine. The yellow color indicates a slightly higher or lower difference, the red color indicates a significantly higher or lower difference, and the green color indicates no difference during the comparison with the conventional CI engine.

Table 4.9 Comparison of methanol engine combustion strategies (Ellis et al. 2018)



Engine Type	Comparison Criteria of the Methanol Engine Combustion Strategies							
	Robustness	Efficiency	Power	Noise	HC	CO	NO_X	Soot
Conventional CI	B	B	B	B	B	B	B	B
MD95 with oxidation catalyst	-	S	-	S	S	S	+	+
MD95 with particulate filter / SCR	-	-	-	S	S	S	+	+
PFI-SI Lean burn	-	S	-	+	-	-	+	+
DISI Lean burn	-	+	-	+	-	-	+	+
Dual-fuel	-	-	-	+	-	-	S	+
DI Dual-fuel	S	S	S	S	-	-	+	+
PPC	-	+	S	-	S	S	+	+

(B = the baseline, − = worse than the baseline, + = better than the baseline, S = the same as the baseline)

The conventional CI engines have a robust operation; therefore, they are preferred to use at heavy duties, such as marine engines. The study compared the robustness of alternative combustion strategies. It can be seen that only DI dual-fuel strategy has the same robustness as the conventional CI engine. All other alternative combustion strategies, except PPC, have slightly lower robustness since these strategies can affect more from the start–stop operation and higher in-cylinder corrosion can be observed (Ellis et al. 2018). PPC has significantly lower robustness, due to its poor low load operation by the cycle-to-cycle in-cylinder pressure variation and sudden high pressure rise rates in the cylinder (Tuner 2015; Ellis et al. 2018).

The engine efficiency is only higher than the conventional CI at DISI lean burn and PPC concepts. PPC strategy has the highest engine efficiency in the study. There is an engine power reduction at all alternative combustion strategies, except DI dual fuel and PPC. The engine power is the same at these combustion strategies. The noise level is slightly higher at the PPC concept since the combustion is more aggressive (Ellis et al. 2018). The PFI-SI lean burn, DISI lean burn, and dual fuel have a lower noise level than the conventional CI.

It can be seen in Table 4.9 that the effect of the MD95 with particulate filter/SCR and PPC on the total emissions is higher than the other combustion concepts. They significantly reduced the NO_X and soot emissions, while HC and CO emissions remained the same as the conventional CI.

The study (Ellis et al. 2018) showed that the PPC strategy can achieve significantly higher engine efficiency than the conventional CI engines without a decline at the engine power. Also, this strategy can substantially reduce NO_X and soot emissions while HC and CO emissions remain the same. The only disadvantage of PPC is the lower robustness, due to its poor operation at the low loads. Although the previous studies (Tuner 2015; Ellis et al. 2018) indicated that the low load operation of the PPC strategy is problematic and results in high engine emissions, later studies (Zincir 2019; Zincir et al. 2019a, b) showed that the PPC strategy can operate well with high engine efficiency and low engine emissions. The next section will contain the findings of these studies.

4.6 The Methanol Partially Premixed Combustion Strategy for Maritime Transportation

The medium to high loads of the methanol PPC engines have been operated without any combustion issues and emission problems at the previous studies (Zincir 2019; Shamun et al. 2016, 2017a, b, 2018; Ellis et al. 2018). The methanol PPC strategy has shown high engine efficiency than the conventional CI engines with lower CO_2 and NO_X emissions. The sulfur-free structure of methanol does not emit SO_X emission, and the low-carbon chain structure of the methanol molecule extremely decreases PM emission formation. The measured PM emission at a methanol PPC study was 0.000004 g/kWh (Tuner et al. 2018), and another study states that the main reason for the PM emissions is from the lubrication oil (Shamun et al. 2017a). The PM emission from the methanol PPC strategy can be assumed as zero, and this is an advantage for using EGR for further decrease of NO_X emission without PM emission trade-off. Otherwise, the low load methanol PPC is problematic due to the possibilities of poor combustion, engine stability problems, high CO, and unburned hydrocarbons. High octane fuels like methanol can cause combustion stability problems by its high auto-ignition resistance (Tang et al. 2017). Also, leaner in-cylinder air–fuel mixtures at the low load operation, which results in very long ignition delay, and retarded combustion phasing, occur combustion stability issues (An et al. 2018).

The methanol PPC was found as a promising combustion strategy in the previous section, except its significantly lower robustness when it is compared with a conventional CI engine. The studies (Tuner 2015; Ellis et al. 2018) indicate that the methanol PPC strategy has a poor operation and high engine emissions at the low load operation. The stable operation of methanol PPC with low engine emissions at medium to high loads has been proofed at the previous studies until now; for this reason only the low load operation will be discussed. This section will give some findings of previous low load studies to contradict these statements and proof that the methanol PPC can be an alternative combustion strategy for the marine engines at all engine loads.

4.6.1 Low Load Performance Comparison of the Conventional CI and Methanol PPC

Maritime transportation routes can be at either open seas or near coastal areas. Ship speed at open seas is at normal speeds, but nowadays reduced speed is used as an operational measure to decrease fuel consumption and mitigate CO_2 emission. This measure is called slow steaming that was proposed by the major shipping company, Maersk, in 2007 (Tezdogan et al. 2015). To reduce ship speed, the engine load is reduced to a certain level. According to MAN B&W, which is the marine engine manufacturer with the largest market share, the slow steaming can safely and reliably be done at below to a 10% engine load by taking necessary precautions (MAN, PrimeServ 2012).

The near coastal areas, such as straits, canals, and ports, are the other areas for the slow speed navigation. The main engine has to operate smoothly and with good combustion stability since these areas are dangerous and risky areas with shallow waters and close distance to the coastal lands. And this type of navigation forms an important part of the ship main engine operation. A study indicates that the low load operation of the main engine constitutes approximately 20% of the total engine operation of a ship (Baldi et al. 2013). In addition to this, emissions from the ships are a crucial problem for near coastal settlements. Maritime transportation activity near coastal areas increases health issues due to the raised harmful emissions, and vegetation areas are degraded.

The methanol PPC strategy can be a solution for greener shipping, especially in the near coastal areas. To find this, Zincir et al. (2019b) made a study about the low load operation of the methanol PPC strategy and the MGO-fueled conventional CI engine was compared. The experimental findings of the methanol PPC strategy are compared with the results of the empirical formulas of the conventional CI engine. The empirical formulas have been used in previous studies (Ammar 2019; Ammar and Seddiek 2017; EEA 2000). Detailed information about the formulas can be found in the study (Zincir et al. 2019b). The methanol PPC experiments were done at 2, 3, and 5 bar gross-indicated mean effective pressure (IMEP) which were assumed as 10, 15, and 25% load, respectively. The SFC, emissions, and efficiency of the engine fueled with marine gas oil were calculated by the empirical and theoretical equations in the study.

Engine performance

The engine performance criterion includes engine stability, gross-indicated efficiency (η_{GIE}), SFC, and specific energy consumption (SEC). The engine stability was measured by the coefficient of variation IMEP (COV IMEP). It is a term representing the stable engine operation, and the top limit is 5% (Przybyla et al. 2016). Equations (4.1)–(4.3) show how to calculate the COV IMEP.

$$\mathrm{IMEP}_n = 1/V_\mathrm{d}\int_0^{720} p\mathrm{d}V \tag{4.1}$$

$$\overline{x} = 1/N\sum_1^N x_i \tag{4.2}$$

$$\mathrm{COV\ IMEP} = \left(\sqrt{\sum_{i=1}^{N}(x_i - \overline{x})^2/N)}/\overline{x}\right)\cdot 100\% \tag{4.3}$$

where N is continuously sampled cycles during the experimental study ($N = 300$) and x_i is IMEP_n of a specific cycle.

Methanol is a high octane fuel that has a high auto-ignition resistance. To overcome this issue to combust methanol in diesel engines, intake air is heated to an optimum point. Intake temperature is one of the important intake parameters for high engine stability. The study showed that higher intake temperature results in more stable engine operation with reduced COV IMEP (Zincir et al. 2019a). The intake temperature was held constant at 150 °C to provide good engine stability.

The η_{GIE} of the methanol PPC strategy was calculated by Eq. (4.4), and the η_{GIE} of the MGO-fueled diesel engine was calculated by Eq. (4.5) (Klaus et al. 2013).

$$\eta_{\mathrm{GIE}_{\mathrm{MeOH}}} = \mathrm{IMEP}\ /\mathrm{FuelMEP} \tag{4.4}$$

$$\eta_{\mathrm{GIE_{MGO}}} = 3600/(\mathrm{LHV} \times \mathrm{SFC}) \tag{4.5}$$

The SFC for the methanol PPC strategy was derived from the experimental study, and the SFC of the MGO-fueled diesel engine was calculated by Eq. (4.6) (Ammar and Seddiek 2017; EEA 2000). The SEC is a measure in MJ/kWh basis which is calculated by Eq. (4.7) (Toolbax and (ETB) 2003).

$$\mathrm{SFC} = 14.1205/\ \%\ \mathrm{load}\ + 205.7169 \tag{4.6}$$

$$\mathrm{SEC} = (\mathrm{SFC} \times \mathrm{LHV})/1000 \tag{4.7}$$

The LHV of methanol is 19.9 and 42.8 MJ/kg for MGO at the SEC calculation.

The COV IMEP of methanol PPC strategy was below 5% at all low loads in the experimental study (Zincir et al. 2019b). It was 3.3%, 2.4%, and 1.4% from 10 to 25% engine load. The MGO-fueled diesel engine has been used for many years in maritime transportation, and there have not any engine stability issues at low load operation. The η_{GIE} of the methanol PPC and the MGO-fueled diesel is shown in Fig. 4.2.

It can be seen in the figure that the methanol PPC strategy has a higher η_{GIE} than the MGO-fueled diesel engine. η_{GIE} is 0.422, 0.459, and 0.463 at the engine loads 10%, 15%, and 25%, respectively, for the methanol PPC while it is 0.240, 0.280, and 0.320 at the same engine loads for the MGO-fueled diesel engine. The high heat of vaporization of methanol formed a cooling effect in the cylinder, reduced the maximum combustion temperature, lowered heat transfer loss, and also decreased

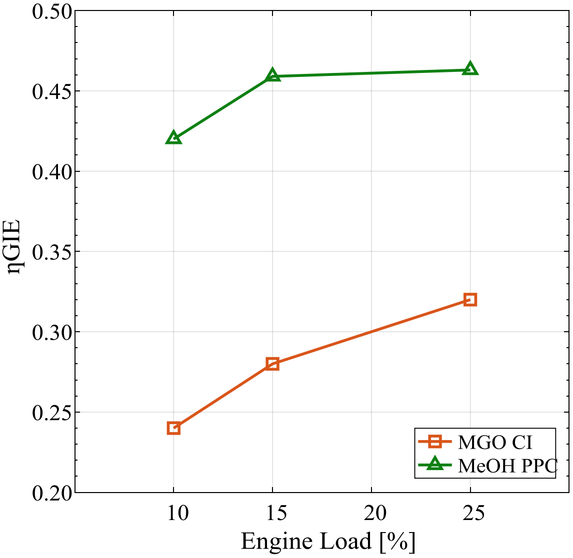


Fig. 4.2 Gross-indicated efficiency comparison of methanol PPC and MGO CI. Values are taken from Zincir et al. (2019b), and a new figure is formed

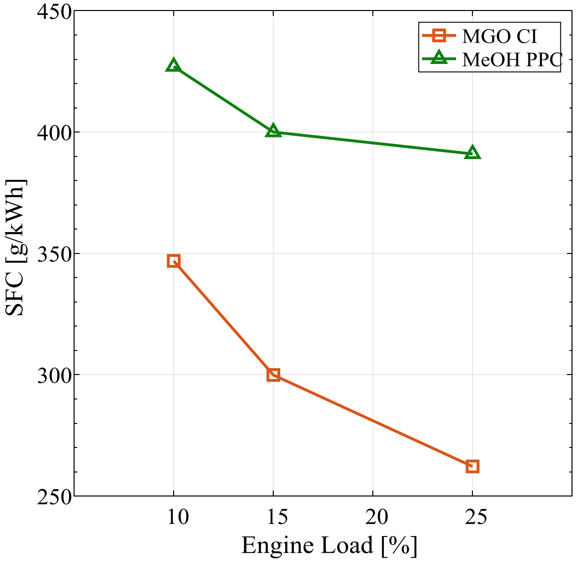


Fig. 4.3 Specific fuel consumption comparison of methanol PPC and MGO CI. (Values are taken from (Zincir et al. 2019b), and a new figure is formed)

compression work that resulted in higher engine efficiency than the MGO-fueled diesel engine. The methanol PPC has precedence over the MGO-fueled diesel engine at low load operations.

Another comparison between the methanol PPC strategy and the MGO-fueled diesel engine is the SFC comparison. Methanol has less than half of the LHV of diesel, so it is obvious that methanol has a higher fuel consumption. Figure 4.3 shows the SFC comparison of two fuels. The MGO-fueled diesel engine has the SFC of 347, 300, and 262 g/kWh, while the methanol PPC has the SFC of 427, 400, and 391 g/kWh from 10 to 25% engine load. The SFC seems higher at the methanol PPC strategy, but the SFC and the SEC should be considered together. Figure 4.4 shows the SEC comparison of both fuels. It can be seen that the methanol PPC strategy has the SEC of 8.5, 8.0, and 7.8 MJ/kWh while the MGO-fueled diesel engine has the SEC of 14.8, 12.8, and 11.2 MJ/kWh. Despite the higher SFC consumption of the methanol PPC, it has lower SEC consumption. This is because of the engine efficiency difference between two combustion strategies at the low load operation. Higher engine efficiency of the methanol PPC strategy provides lower energy required to provide the same engine load. Again, it is proofed that the methanol PPC concept is a promising tool for the stable and efficient combustion at the low load operation of the marine diesel engines.

Engine emissions

The regulated emissions in maritime transportation are CO_2, NO_X, SO_X, and PM emissions. The study (Zincir et al. 2019b) compares emissions of the methanol PPC strategy and the MGO-fueled diesel engine. The emissions of the methanol PPC strategy, except SO_X and PM emissions, were measured during the experiments. On

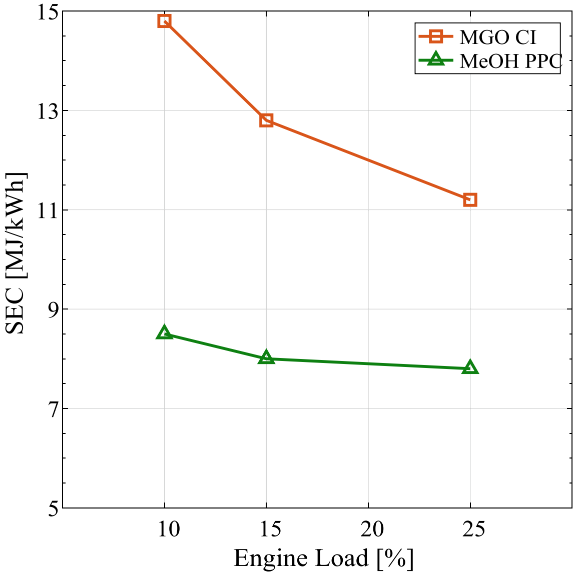


Fig. 4.4 Specific energy consumption comparison of methanol PPC and MGO CI. (Values are taken from (Zincir et al. 2019b), and a new figure is formed.)

Table 4.10 Emission factor coefficients (Revised from Zincir et al. 2019b)

Coefficient	NO_X	SO_X	PM	CO_2
a	0.1255	2.3735	0.0059	44.1
z	1.5	n/a	1.5	1.0
b	10.4496	−0.4792	0.2551	648.6

the other hand, the emissions of the MGO-fueled diesel engine were calculated by the empirical formulas. Equations (4.8) and (4.9) with the coefficients in Table 4.10 were used to calculate the emissions (Zincir et al. 2019b; Ammar 2019; Ammar and Seddiek 2017; ICF 2009).

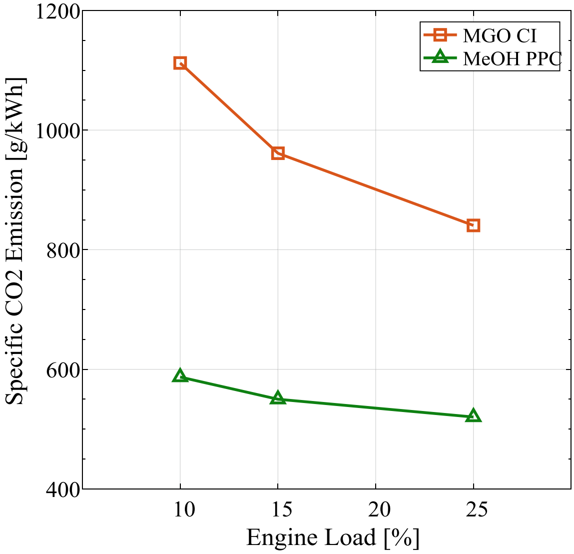
$$E = a(\%\text{load})^{-z} + b \tag{4.8}$$

$$E_{\text{SO}_x} = a(\text{SFC} \times S\%) + b \tag{4.9}$$

where *a*, *z*, and *b* are the emission factor coefficients. *S*% is the fuel sulfur fraction that was taken as 0.1% to represent low-sulfur marine gas oil (LSMGO) and comply with the new sulfur regulation limit.

The specific CO_2 emissions of the methanol PPC strategy and the MGO-fueled diesel engine are shown in Fig. 4.5. The specific CO_2 emissions of the MGO-fueled diesel engine are 1112, 961, and 841 g/kWh, while it is 587, 550, and 520 g/kWh for methanol PPC at 10%, 15%, and 25% engine load, respectively. CO_2 emission is related to fuel consumption and the carbon content of the fuel. Although the methanol

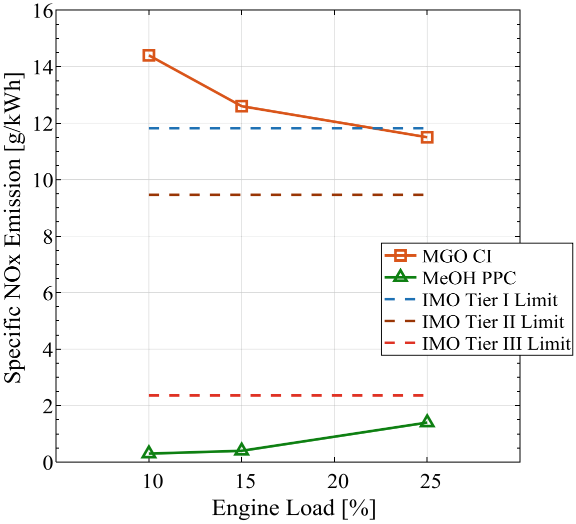
Fig. 4.5 Specific CO_2 emissions of methanol PPC and MGO CI. Values are taken from (Zincir et al. 2019b), and a new figure is formed



PPC strategy has a higher SFC than the MGO-fueled diesel engine, the carbon content of methanol is lower than MGO. The carbon content of methanol is 37.5%, while it is 85.7% for the MGO (Systems and (GCS) 2019). Besides, the methanol PPC engine efficiency is higher than the MGO-fueled diesel engine which results in lower CO_2 formation.

Figure 4.6 shows NO_X emissions of the methanol PPC strategy and the MGO-fueled diesel engine. The MGO-fueled diesel engine has the NO_X emission of 14.4,

Fig. 4.6 Specific NO_X emissions of methanol PPC and MGO CI. Values are taken from Zincir et al. (2019b), and a new figure is formed



12.6, and 11.5 g/kWh from 10 to 25% engine load, respectively. The engine was considered operating at 800 rpm which was the same as the experimental studies with the methanol PPC. The IMO Tier I Limit is 11.8 g/kWh for the engine at 800 rpm. The MGO-fueled diesel engine does not fulfill with even the IMO Tier I Limit at 10 and 15% engine loads. However, the methanol PPC concept complies with the IMO Tier III Limit of 2.4 g/kWh. The NO_X emissions are 0.3, 0.4, and 1.4 g/kWh between 10 and 25% engine loads. The NO_X formation depends on high in-cylinder temperature. The high heat of vaporization of methanol decreases maximum combustion temperature, and it results in a lower NO_X formation. Also, the methanol PPC strategy has a shorter burn duration which means the maximum in-cylinder temperature period is shortened. The methanol PPC strategy complies with the recent NO_X emission limit at the low load operation without any after-treatment system.

The SO_X emission from the marine engines is more important after the new IMO Sulfur Cap regulation entered into force on January 1, 2020. Methanol has a sulfur-free structure that does not emit SO_X emission. It is naturally the SO_X emission regulation compliant fuel. Figure 4.7 shows the SO_X emission comparison of the methanol PPC strategy and the MGO-fueled diesel engine. The methanol PPC plot is drawn as zero at all loads in the study. The MGO in the study (Zincir et al. 2019b) was assumed as LSMGO (0.1% sulfur in the fuel) and complied with the sulfur regulation. The specific SO_X emission of the MGO-fueled diesel engine is 0.34, 0.23, and 0.14 g/kWh between 10 and 25% engine loads, and complies with the SO_X ECA Limit. Figure 4.8 shows the specific PM emissions of methanol PPC strategy and MGO-fuelled diesel engine. Methanol fuel does not emit PM emission due to its sulfur-free structure. The PM emission has the same ECA and non-ECA limits. It can be seen that the MGO-fuelled diesel engine does not comply with the PM

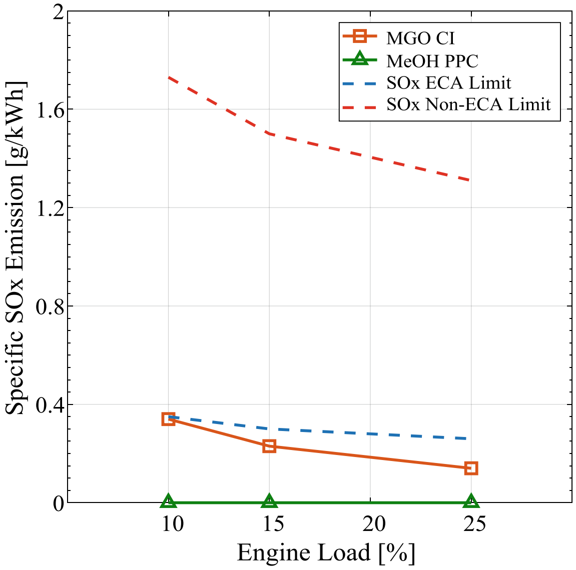
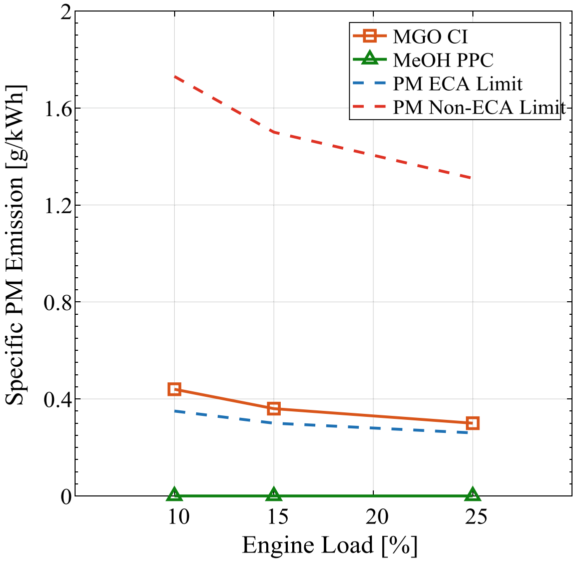


Fig. 4.7 Specific SO_X emissions of methanol PPC and MGO CI. Values are taken from Zincir et al. (2019b), and a new figure is formed

Fig. 4.8 Specific PM emissions of methanol PPC and MGO CI. Values are taken from Zincir et al. (2019b), and a new figure is formed



ECA limit. The MGO-fueled diesel engine has the PM emissions of 0.44, 0.36, and 0.30 g/kWh which are above the PM ECA limit of 0.35, 0.30, and 0.26 g/kWh at 10%, 15%, and 25% engine load.

The methanol PPC strategy proved itself at medium to high engine load at the previous studies. Also, it showed good emission performance when it was compared with the MGO-fueled diesel engine at the low load operation. Methanol has lower carbon content than the MGO, and the PPC strategy has higher gross-indicated efficiency that resulted in lower CO_2 emission than the MGO-fueled diesel engine. The NO_X emission was lower than the IMO Tier II Limit for the methanol PPC strategy, and the sulfur-free structure of methanol does not emit SO_X and PM emissions. The methanol PPC strategy is a promising fuel combustion strategy combination for the marine engines at the low load operation.

4.7 Summary

This chapter covered the status of maritime transportation, international maritime rules and regulations, emission mitigation technologies and methods on ships, methanol at maritime transportation, methanol properties, and combustion concepts, and the methanol partially premixed combustion strategy for maritime transportation.

Maritime transportation is an important way to perform international trade. It constitutes 90% of worldwide trade by 96,295 ships in various tonnages. Ships consume a huge amount of fuel and emit a high level of pollutants to the atmosphere. To decrease shipboard emissions, IMO has been working on international maritime emission rules and regulations. The international maritime emission rules and regulations are becoming stricter day by day. The chapter gave detailed information about recent rules and regulations about CO_2, NO_X, SO_X, and PM emissions. Emission mitigation technologies and methods have been used to comply with the recent rules and regulations. There are design measures, engine and engine room machinery modifications, operational measures, and new technologies to reduce CO_2 emissions from ships, and pre-combustion, combustion intervention, and after-treatment methods to decrease NO_X emissions from ships. SO_X emissions are mitigated by using low-sulfur conventional fuels, SO_X scrubbers, or sulfur-free alternative fuels. Alternative fuels can reduce all types of emissions at once without any other methods. The most popular alternative fuels at maritime transportation are LNG and methanol. Methanol was compared with LNG and some emission mitigation technologies and was found as the most promising emission mitigation element.

Maritime-based methanol projects and methanol-fueled commercial applications are in increasing trend. The IGF Code entered into force in January 2017 by IMO. The Code contains mandatory criteria for the design and installation of machinery, equipment, and systems for ships using gases or other low-flashpoint fuels, such as methanol. There are also the classification society rules and guidelines for methanol.

Methanol emits low CO_2 and NO_X emissions and zero SO_X and PM emissions. This is important to comply with the recent international emission rules and regulations. Methanol provides higher engine efficiency than diesel thanks to its unique properties. Methanol has similar physical properties to conventional marine fuels, and it can be kept at the same bunker tanks after minor modifications. The only disadvantage is its LHV is less than half of the LHV of diesel, so double the onboard storage volume of the conventional fuel is required for the same distance. Methanol is environmentally friendly because it is biodegradable and does not give much damage to sea ecology. On the other hand, it is toxic for humans, and the ship crew has to be careful during the methanol operation.

Methanol can be combusted at diesel engines by various combustion strategies. The most promising combustion strategy is PPC. This strategy can provide higher engine efficiency than the conventional CI with no power reduction. Besides, it can reduce NO_X and soot emissions while HC and CO emissions remain the same. The methanol PPC strategy proved itself at medium to high engine loads. The only drawback according to the previous studies is lower robustness than the conventional CI, because of its poor low load performance. But it was shown in the chapter that the methanol PPC can be operated at the low loads with good engine stability of 3.3%, 2.4%, and 1.4%, high engine efficiency (0.422, 0.459, and 0.463) than the conventional CI (0.240, 0.280, and 0.320) at the engine loads 10%, 15%, and 25%, respectively.

The MGO-fueled diesel engine has the SFC of 347, 300, and 262 g/kWh, while the methanol PPC has the SFC of 427, 400, and 391 g/kWh at the same engine loads. On the other hand, the SEC of the methanol PPC is lower than the MGO-fueled diesel engine with 8.5, 8.0, and 7.8 MJ/kWh while it is 14.8, 12.8, and 11.2 MJ/kWh at the same engine loads. Although the SFC is higher at the methanol PPC, the high engine efficiency provides lower SEC.

The methanol PPC strategy has lower emissions than the MGO-fueled diesel engine, which complies with IMO Tier III Limit and IMO Sulfur Cap. The methanol PPC strategy has 587, 550, and 520 g/kWh CO_2 emissions and 0.3, 0.4, and 1.4 g/kWh NO_X emissions, while the MGO-fueled diesel engine has 1112, 961, and 841 g/kWh CO_2 emissions and 14.4, 12.6, and 11.5 g/kWh NO_X emissions at 10%, 15%, and 25% engine load, respectively. The SO_X and PM emissions are zero for the methanol PPC strategy.

Methanol is one of the promising alternative fuels for maritime transportation and the usage of methanol as a fuel will be increased in the future. Using biomethanol will further decrease CO_2 emissions drastically. In addition to this, the PPC strategy can be used at the marine engines with methanol to provide high engine efficiency and low engine emissions.

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