Chapter 3
DME as a Green Fuel for Transport Sector

Ayush Tripathi and Avinash Kumar Agarwal

Abstract Transport sector is one of the largest contributor to global greenhouse gas (GHG) emissions. GHG emissions are the leading cause of global warming. Various government bodies have imposed strict emission legislation across the worldwide on industries with large carbon footprints. Therefore, the transport sector is greatly strained to meet stringent emission norms. Crude oil refined products such as diesel and gasoline are the primary fuels used in the transport sector. Greener e-fuels with low carbon footprint are suitable alternatives to replace the fossil fuels, which can reduce the life cycle CO_2 emission and meet emission norms. Dimethyl ether (DME) is one such greener alternative to diesel. Diesel-fuelled CI engines are majorly emitting the NO_x and soot emissions. DME can reduce NO_x and soot emissions simultaneously. The molecule of DME does not contain a C–C bond. Therefore, it resists the formation of soot precursors. High-temperature zones are the ideal zones for NO_x formation in an engine combustion chamber. The high latent heat of vaporisation of DME reduces the in-cylinder temperatures; hence, decreases the NO_x formation. DME also shows a high cetane number (CN), molecular oxygen, shorter ignition delay, and superior atomisation characteristics than baseline mineral diesel. However, lower viscosity, high vapour pressure, longer fuel injection delay due to higher compressibility, and lower lubrication properties of DME makes it difficult to be used by diesel fuel injection equipment (FIE). Certain modifications are required in diesel FIE to operate on DME. This chapter briefly discusses the various modifications required in FIE to utilise DME. The effects of superior properties of DME on various engine parameters are also described.

Keywords GHG emissions · E-fuels · DME · Life cycle analysis · Soot · Life cycle · Fuel injection equipment (FIE)

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Abbreviations

ASTM	American Society for Testing and Materials
aTDC	After Top Dead Centre
BSFC	Brake Specific Fuel Consumption
BTE	Brake Thermal Efficiency
bTDC	Before Top Dead Centre
CAD	Crank Angle Degree
CHR	Cumulative Heat Release
CH_4	Methane
CI	Compression Ignition
CN	Cetane Number
CNG	Compressed Natural Gas
CO	Carbon Monoxide
CO_2	Carbon Dioxide
DEE	Diethyl Ether
DME	Dimethyl Ether
DS	Dry Soot
EGR	Exhaust Gas Recirculation
EGT	Exhaust Gas Temperature
EPA	Environmental Protection Agency
FIE	Fuel Injection Equipment
GDP	Gross Domestic Product
GHG	Greenhouse gases
HP	High Pressure
HRR	Heat Release Rate
HTR	High-Temperature Reactions
H_2	Hydrogen
IC	Internal Combustion
IMEP	Indicated Mean Effective Pressure
LHV	Lower Heating Value
LNT	Lean NO_x Trap
LP	Low Pressure
LPG	Liquified Petroleum Gas
LTR	Low-Temperature Reaction
MMT	Million Metric Ton
NBR	Nitrile Butadiene Rubber
NOAA	National Oceanic and Atmospheric Administration
NOx	Oxides of Nitrogen
NTP	Normal Temperature Pressure
ON	Octane Number
OSHA	Occupational Safety and Health Administration
PAHs	Polycyclic Aromatic Hydrocarbons
PCCI	Premixed Charge Compression Ignition

PM	Particulate Matter
PPCCI	Partially Premixed Charge Compression Ignition
RoPR	Rate of Pressure Rise
SCR	Selective Catalytic Reduction
SoI	Start of injection
SOx	Oxides of Sulphur
SO_2	Sulphur Dioxide
UK	United Kingdom

3.1 Introduction

The transport sector plays a vital part in the GDP growth of any country. This sector contributes ~6.4% to the GDP of India (India Planning Commission 2007). The average annual growth rate of the transport sector is much higher than India's GDP growth rate. The transport sector consumes crude oil-origin fuels such as diesel and gasoline. The transport sector is responsible for ~13.5% of energy-related CO_2 emissions in India (New Climate Institute 2020). India is the third-biggest CO_2 emitter in the world, after China and USA. India committed to achieve the carbon neutrality by 2070 at Glasgow's COP26 climate change conference. Therefore, Indian government aims to reduce and eventually eliminate tailpipe emissions from the transport sector without impacting the economy. In 2019, India imported crude oil worth US$ 105 billion (https://energy.economictimes.indiatimes.com/news/oil-and-gas/indias-crude-oil-import-bill-set-to-rise-20-to-105-billion-in-fy19/63881639). Crude oil imports accounted for ~4% of the GDP. Reducing the crude oil import would help cut down the import bill and increase the forex reserve in India.

Rapid depletion of fossil sources due to rising energy consumption has become a primary global concern in the twenty-first century since the reserves are finite. At the present consumption rates, all known fossil fuel reserves will deplete in the next 45 years (https://www.worldometers.info/oil/#:~:text=World%20Oil%20Reserves&text=The%20world%20has%20proven%20reserves,levels%20and%20excluding%20unproven%20reserves). A higher consumption rate is particularly concerning because fossil fuel production/burning emits greenhouse gases (GHG), which cause global warming. Worldwide CO_2 emissions are rapidly increasing (Fig. 3.1) due to anthropogenic activities.

According to the National Oceanic and Atmospheric Administration (NOAA), this has resulted in an average global temperature rise of 0.8 °C over the last 100 years. Environmental Protection Agency (EPA) claims that the sea level has risen by 20 cm since 1970 (https://www.livescience.com/37057-global-warming-effects.html). At the current rate of GHG emissions, several weather forecast models anticipate a 2 °C rise in average earth temperature, which might cause fast melting of the polar ice. This forecast indicates a 3-feet rise in the sea level by the end of this century (https://www.livescience.com/37057-global-warming-effects.html; https://clintonwhitehouse5.archives.gov/Initiatives/Climate/next100.html). This sea level rise can sweep away many island nations and large coastal towns and submerge large land areas worldwide, creating mayhem.

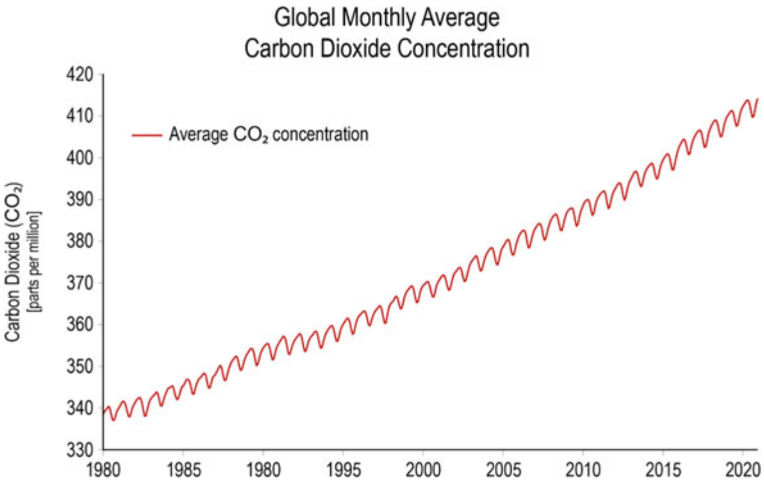
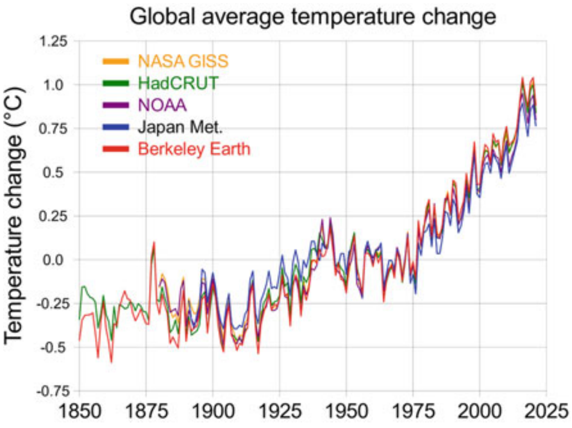


Fig. 3.1 Increase in global CO_2 emissions since 1980 (https://www.globalchange.gov/browse/indicators/atmospheric-carbon-dioxide)

Extreme weather occurrences such as storms, droughts, and flooding would be exacerbated by rising global average temperature (Fig. 3.2) (https://www.livescience.com/37057-global-warming-effects.html). Globalising carbon-neutral fuels and sustainable technologies at the right moment could help to reduce the global warming by 0.50 °C (https://www.europarl.europa.eu/news/en/headlines/society/20190926STO62270/what-is-carbon-neutrality-and-how-can-it-be-achieved-by-2050). For sustainable development, the production of alternative transport fuels should also be carbon neutral.

Fig. 3.2 Average global temperature rise (https://en.wikipedia.org/wiki/Global_surface_temperature)



Many nations are implementing plans to cut net GHG emissions and achieve the carbon neutrality by 2050. Like Norway and the UK, many European countries want to phase out fossil-fuel-powered vehicles by 2035 (https://www.roadtraffic-technology.com/features/european-countries-banning-fossil-fuel-cars/). There is a push to reduce the net GHG emissions by at least 55% within 2030 and achieve the carbon neutrality by 2050 (https://eur-lex.europa.eu/legal-content/en/TXT/?uri=CELEX%3A52021PC0559). The use of clean alternate fuels which emits fewer GHGs than conventional fuels is one way to achieve the carbon neutrality. GHG emissions from the transport industry are significant. Throughout worldwide many governments are enforcing the strict emission standards to reduce GHG emissions from the transport sector. Europe has implemented EURO emission norms for internal combustion (IC) engine-powered vehicles to reduce the GHG emissions. In Europe, new on-road vehicles must comply with EURO-VI emission norms (https://eur-lex.europa.eu/legal-content/en/TXT/?uri=CELEX%3A52021PC0559).

3.2 Challenges for Compression Ignition (CI) Engines

CI engines are a popular choice for heavy-duty transport power plants due to their superior thermal efficiency, lower fuel consumption, and high power output than SI engines (https://www.worldometers.info/oil/#:~:text=World%20Oil%20Reserves&text=The%20world%20has%20proven%20reserves,levels%20and%20excluding%20unproven%20reserves). The CI engines are mostly fuelled by diesel. Diesel-fuelled CI engines emit high NO_x and soot. The main cause of increased soot emission is an inadequate fuel-air mixture forming several oxygen-deficient and fuel-rich zones. In the fuel-rich zones, long-chain C–C bonds aid in soot formation. This can be resolved by using an oxygenated fuel such as DME. CI engines require various exhaust gas after-treatment systems to comply with stringent emission norms. A significant reduction in pollutants is necessary to comply with future emission standards and to compete with the BEVs. DME is an excellent replacement for diesel for reducing NO_x emissions. Soot precursors hardly form due to the absence of a C–C bond in the molecular structure of DME. Therefore, DME combustion produces very low soot. These characteristics make DME a superior alternative for CI engines to replace the mineral diesel.

3.3 Alternative Fuel Scenario

India implemented Bharat stage-VI emission norms to regulate emissions from IC engine-powered vehicles in April 2020. The transport industry must also investigate new, alternative, low-carbon fuels to reduce GHG emissions and comply with prevailing and upcoming stringent emission norms. Low carbon fuels are the such kind of fuels which produce less CO2 while undergoing the combustion. These fuels do not require the large modifications in existing infrastructure. These low carbon fuels lie in the category of electro fuels (e-fuels) whenever produced via carbon capture methods because CO2 is being consumed during the production process. Therefore, manufacturing of e-fuels is carbon negative process. While performing the life cycle analysis, carbon footprint of e-fuels is near zero unlike low carbon fuels whose life cycle carbon footprint is lower than crude oil derived conventional fuels but significantly higher than e-fuels. Therefore, e-fuels like e-DME, e-Methanol, e-Methane are the suitable choice for transport industry to meet the goal of becoming carbon-neutral by 2050. European union exempt e-fuels from 2035 ban on new sales of combustion-engine cars.

Using locally available alternative low-carbon fuels to replace the diesel and gasoline effectively can reduce the dependence on crude oil. Such alternative fuels include Dimethyl ether (DME), Methanol, Ethanol, Diethyl ether (DEE), Green Hydrogen (produced from renewable sources), Hydrotreated Vegetable Oil, etc. These fuels are produced in India using different methods and feedstocks, e.g., methanol from coal gasification, ethanol from sugarcane, and DME from dehydration of methanol. India has a vast reserve of high-ash coal and adequate sugarcane production. These fuels can be produced in abundance from these resources, reducing the nation's dependence on crude oil imports. Adding 15% methanol to gasoline can reduce crude oil import by at least 15%. This would result in a 20% reduction in GHG emissions, including the reductions in NO_x, PM, and SO_x emissions, improving urban air quality. By mixing 20% DME in LPG, Rs 6000 crore can be saved annually (https://www.niti.gov.in/methanol-economy). India has a 2 MMT per annum installed capacity for methanol production, and DME production facilities are under commissioning. In collaboration with Israel, the Indian government is setting up five methanol and DME production plants. According to national green hydrogen mission, Indian government is planning to develop the green hydrogen production of 5 MMT (Million Metric Tonne) per annum. However, India doesn't have any production facility for Hydrotreated Vegetable Oil.

3.4 DME: An Alternative Fuel

Regulatory bodies impose emission legislations to cut GHG emissions from the road transport sector. It also helps achieve the mission objective of restricting the global temperature rise within the 1.5 °C limit. With this perspective, automotive manufacturers are working on producing more efficient engines while meeting the prevailing emission legislation. Among the two distinct engine types, diesel-fueled CI engines emit higher soot and NO_x than SI engines (Kim et al. 2008a). Due to their trade-off, soot and NO_x emissions cannot be reduced simultaneously (Kim et al. 2008a). By lowering the in-cylinder temperature, technologies such as exhaust gas recirculation (EGR) minimize NO_x emissions (Yoon et al. 2013). However, EGR deteriorates the combustion and increases soot emissions from CI engines. DME is the most suitable alternative to reduce soot and NO_x emissions simultaneously. Soot

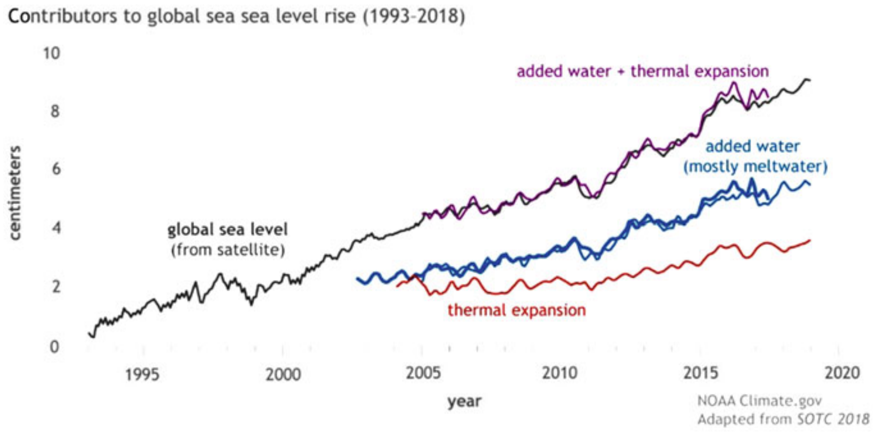


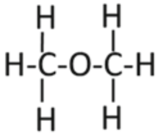
Fig. 3.3 Average global sea level rise (https://www.climate.gov/media/12868)

precursor formation is suppressed in the DME engine due to the absence of C–C bonds in its molecule. Therefore, soot emissions from DME engines are negligible. In addition, EGR significantly reduces NO_x emissions without increasing the soot in DME combustion. This section discusses the properties, advantages, and drawbacks of DME use in CI engines (Fig. 3.3).

DME-fuelled vehicles have shown promising performance and emission characteristics compared to conventional diesel. Essential parameters for ensuring the sustainability of alternative fuels include their production from renewable sources, compatibility with engine components, economic viability, lower overall carbon footprint, and higher H/C ratio (Valera and Agarwal 2019). Other properties such as fuel-bound oxygen and lack of C–C bond make them more attractive. DME is the simplest of all ethers, having fuel-bound oxygen without a C–C bond. DME may meet the requirement of a sustainable CI engine alternate fuel. It can reduce emissions of NO_x and PM. However, substantial adjustments are required in CI engines, particularly in FIE (Fig. 3.4).

DME has physical properties similar to LPG (Fig. 3.5). LPG is mainly propane and butane. Storage, transport and fuel handling of DME are practically equivalent to LPG due to their almost similar physico-chemical properties (Park and Lee 2014). The ignition delay of DME is significantly lower than diesel (Fig. 3.6). Superior spray atomisation characteristics of DME led to better fuel-air mixing and short ignition delay. The low boiling point and viscosity of DME causes the quick spray atomization and fast vaporisation of fine size droplets. Therefore, an efficient mixing

Fig. 3.4 Molecular structure of DME



of fuel vapors with surrounding air takes place easily. High CN and low auto-ignition temperature of DME plays a vital role in reducing the ignition delay compared to diesel.

DME is an opaque gaseous ether at 0.1 MPa and 298 K. DME converts from vapour to liquid phase when compressed to pressure above 0.5 MPa at atmospheric temperature. The viscosity of DME is less than a tenth of conventional diesel. DME's low viscosity is a reason for poor lubricity, leading to friction, wear and internal leakages in the FIE. Adding lubricity additives to DME is a way to resolve lubricity issues. DME harms several types of plastics and rubbers. DME dissolves in all known elastomers used in diesel FIE. Teflon and Buna-N rubber are DME-compatible materials (MacFarlane 1965). However, the creep and stiffness properties of Teflon make it unsuitable as a sealing material for use in the FIE (Sorenson 2001). Sivebaek et al. (2001) observed premature failure of diesel FIE as DME lacks to offer the same levels of viscosity or lubricity as mineral diesel. It may be challenging to

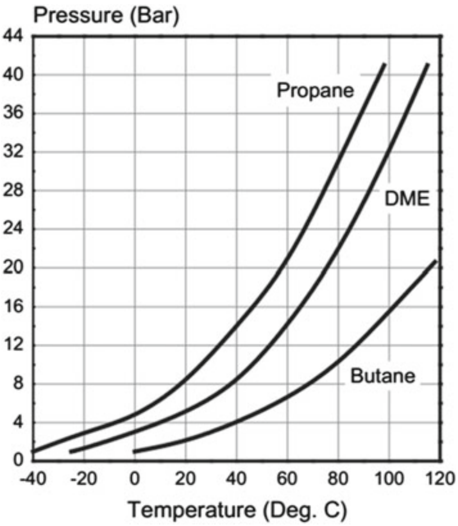


Fig. 3.5 Variations in vapour pressure of propane, DME and butane w.r.t. temperature (Park and Lee 2014)

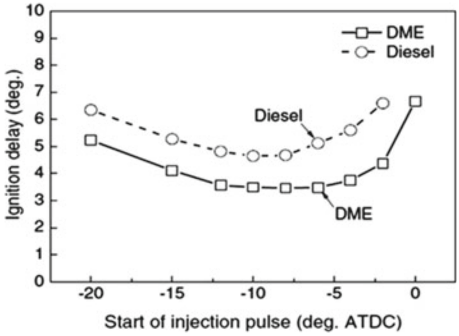


Fig. 3.6 Ignition delay of diesel and DME at varying fuel injection timings (Park and Lee 2014)

increase the lubricity of DME to acceptable levels. However, modifying the pump designs to accept DME could be a feasible technical solution. DME has a bulk modulus of 0.637 MPa, which is ~1/3 of mineral diesel (1.49 MPa) (Kim et al. 2008b). The compressibility of DME is higher than diesel due to its lower elastic modulus (Fig. 3.12). Therefore, a larger compression energy is required by the fuel pump for DME than mineral diesel. In a closed system, the compression energy required for DME is 3.2 times more than dodecane at a compression pressure of 25 MPa at 323 K (Park and Lee 2013). Due to a large cetane number and low injection delay of DME, its ignition occurs earlier than mineral diesel. The combustion process gets completed faster for DME compared to baseline diesel. Flash boiling provides greater fuel and air mixing due to the low boiling point of DME (Kim et al. 2007a).

Spray tip penetration for DME is lesser than mineral diesel due to its low boiling point and kinetic viscosity which leads to improved atomisation and fast droplet mass dispersion compared to diesel. The finer DME droplets are expected to decelerate faster than diesel while approaching downstream. Therefore, DME has short spray tip penetration than diesel fuel under the same fuel injection conditions (Fig. 3.7). The high evaporation rate and small droplet size of DME also leads to superior charge mixing and mixture homogeneity. This leads to improved combustion efficiency and low combustion noise than mineral diesel. Spray tip penetration of DME decreases as the surrounding pressure increases primarily due to the high ambient gas density suppresses the spray growth (Park and Lee 2014; Kim et al. 2009). Spray cone angle of DME is marginally higher than diesel. DME spray has less radiative heat loss compared to diesel due to the non-luminous flame. DME spray evaporation rate is higher than spray breakup rate which avoids the secondary spray breakup in DME, unlike diesel.

DME is a fluorocarbon propellant substitute due to its low vapour pressure, strong solvency properties and pleasant atmospheric behaviour (Sorenson 2001).

Figure 3.8 shows the global share of DME according to its usage. Most DME is used as an LPG-DME blend. A similar LPG and DME vapour pressure makes it suitable for blending both (Fig. 3.5).

DME is widely used in aerosol sprays, and its second-largest application is in the aerosol industry. The transport sector utilises only a tiny fraction of globally

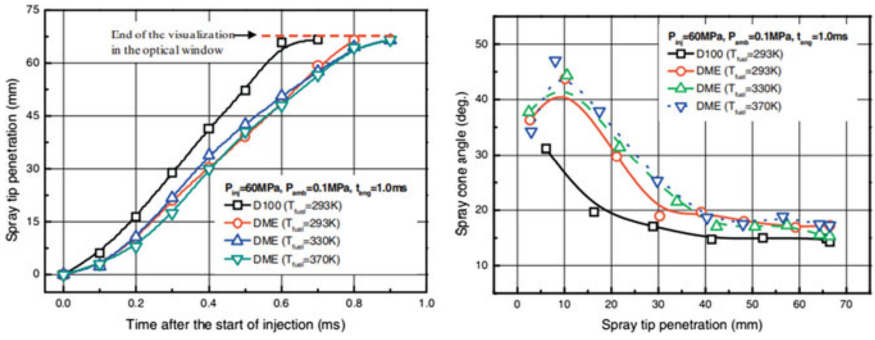


Fig. 3.7 Spray tip penetration and spray cone angle of diesel and DME (Park et al. 2010)

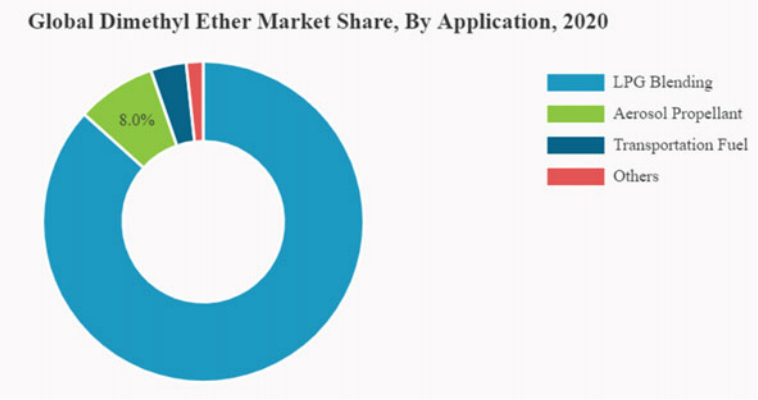


Fig. 3.8 Global market share of DME by its applications (https://www.fortunebusinessinsights.com/dimethyl-ether-market-104309)

produced DME. However, DME utilisation in transport sector is increasing rapidly due to its superior combustion and emission characteristics. The C/H ratio of the fuel affects the water content in the exhaust and hence, DME-fuelled engines show more water in exhaust than in mineral diesel (Oguma et al. 2005).

3.5 DME: Production Routes

China is the biggest producer of DME. Japan also has DME production facilities. Many other countries, namely North America, Uzbekistan, Indonesia, and Trinidad and Tobago, are planning to install DME production facilities. Sweden is home to the world's first bio DME plant. Annually ~5 to 9 million tons of DME is produced across the worldwide (Szybist et al. 2014). Several renewable and non-renewable methods are available for DME production (Kumar and Agarwal 2021). Using suitable catalysts, DME can be produced from fossil feedstocks such as coal and natural gas (Jang et al. 2009). Moreover, DME can be produced from renewable energy sources such as biomass (via methanol route), solar, and wind (Fig. 3.9). An electrolyser powered by electricity generated using renewable sources of energy such as wind farms and photovoltaics can produce the hydrogen in a syngas mixture for synthesis of DME. Therefore, DME can also be called a renewable energy storage pathway (Falco 2017). Approximately 1.4 tons of methanol is required to produce 1 ton of DME.

DME can be produced by two major pathways (Agarwal et al. 2017): (a) the Dehydration of Methanol; and (b) Direct conversion to DME from syngas. Syngas is a mixture of CO, H_2, CO_2, CH_4 and other gases, wherein the share of CO is the maximum (~30–60%).

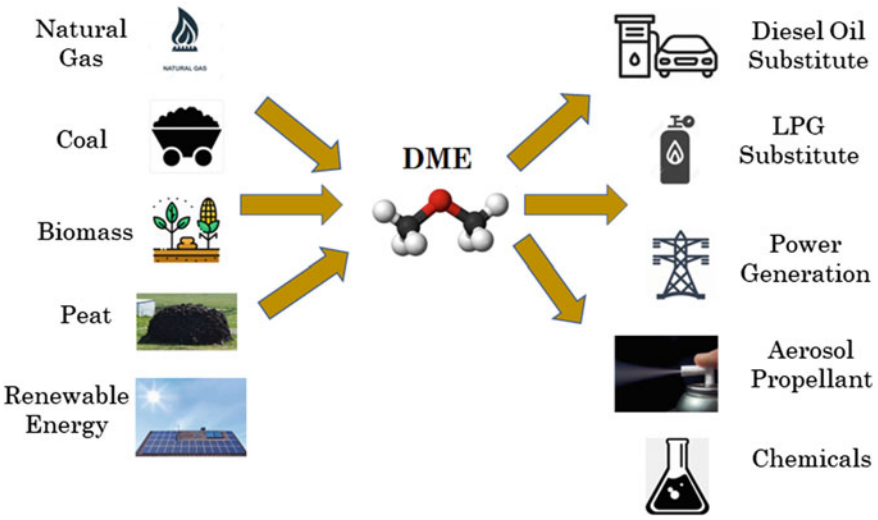


Fig. 3.9 Different production pathways and applications of DME

(a) **Dehydration of Methanol**: Methanol is first produced from syngas and then dehydrated into DME. This is the two-step process, wherein methanol production from syngas and dehydration of methanol to produce DME occurs in different reactors. This process is shown in Eqs. 3.1, 3.2 and 3.3, wherein the first two reactions show methanol production from syngas, and the third reaction shows methanol dehydration to produce DME.

$$CO + 2H_2 \rightarrow CH_3OH \tag{3.1}$$

$$CO_2 + 3H_2 \rightarrow CH_3OH + H_2O \tag{3.2}$$

$$2CH_3OH \rightarrow CH_3OCH + H_2O \tag{3.3}$$

(b) **Direct DME Conversion**: In this process, DME production is done using bi-functional catalysts such as Cu/ZnO. This is a one-step DME production process, given by Eq. 3.4.

$$2CO + 6H_2 \rightarrow CH_3OCH + 3H_2O \tag{3.4}$$

Syngas is fed at 5 MPa pressure and 270 °C for direct production of DME because it requires a high kinetic reaction rate (Falco 2017). This reaction is highly exothermic; therefore, extreme caution is needed to avoid any chances of an accident. A direct synthesis reaction is preferred over an indirect synthesis reaction for DME production due to the lesser wastage of natural gas. Most companies worldwide produce DME using a one-step or two-step DME production process. Companies such as NKK, Air products, Topsoe, Korea Gas Co., and JFE Ho produce DME using a one-step process, whereas Toyo, MGC, Lurgi, and Udhe produce DME using a two-step process (Falco 2017).

DME Production from Renewable Energy Sources

DME Production From biomass: Renewable energy sources like biomass, solar, and wind can produce the reactants used in the DME synthesis process. DME functions as a liquid energy vector in this approach, storing renewable energy in a high-energy density fuel (Falco 2017).

Figure 3.10 shows the schematic of the production of DME from biomass. For biomass resources such as agro-residues, energy crops, and forest residues. For biomass resources such as organic trash, sewage and manure, anaerobic digestion combined with pyrolysis produce syngas. The synthesis process is governed by the syngas to produce DME.

DME Production from Solar Energy: Syngas is a mixture of CO and H_2. Hydrogen for the syngas can be produced using an electrolyser, as shown in Fig. 3.11.

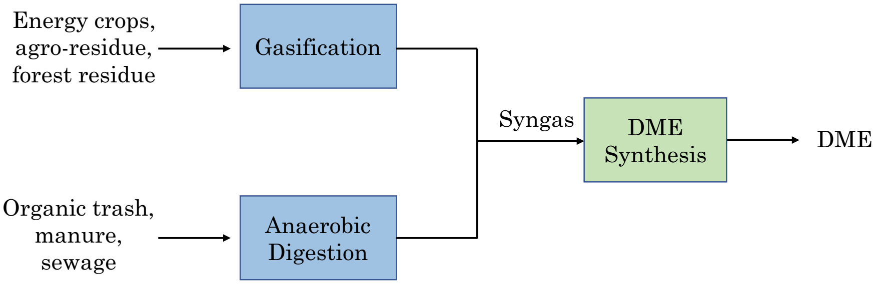


Fig. 3.10 DME production from biomass

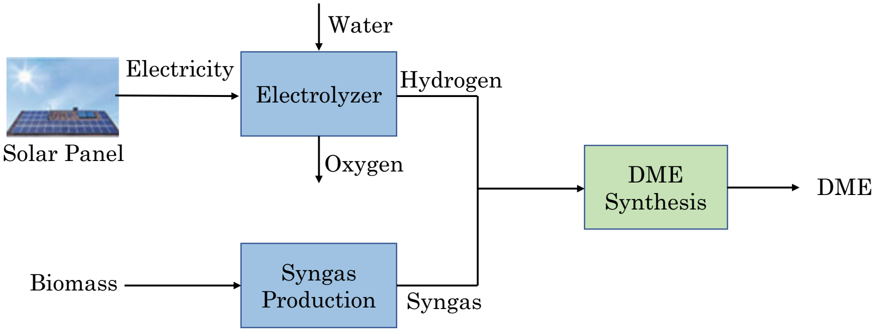


Fig. 3.11 DME production from solar energy

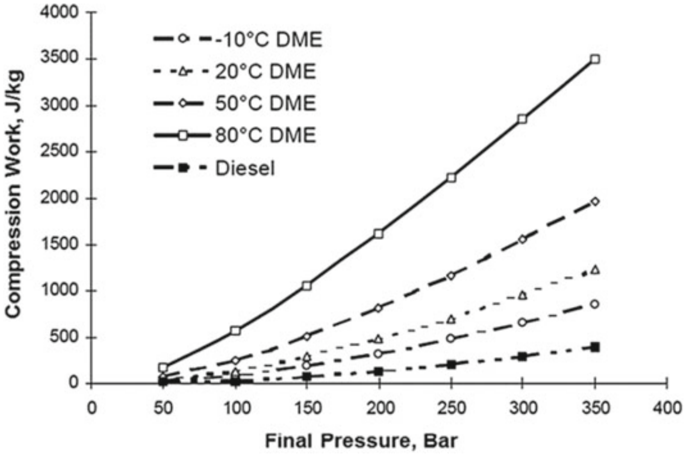


Fig. 3.12 Compression work for diesel and DME at different temperatures (Park and Lee 2013)

The electrolyser operates using solar power-generated renewable electricity. The hydrogen then mixes with the CO/CO_2 produced by biomass gasification to correct the stoichiometry, which is suitable for DME production. Renewable energy, such as solar energy, can be stored as high-energy density liquid fuel DME. DME, like liquid fuels, can be more easily stored and transported than hydrogen, which has several issues related to its storage and distribution. Therefore, on a large scale, DME can easily emerge as a suitable carrier and storage medium of renewable energy and its use in the transport sector (Fig. 3.12). DME produced from renewable energy sources is also termed as e-DME.

3.6 DME: Health, Environmental and Safety Effects

DME is a colourless liquid or gas-phase fuel, depending on the storage conditions. Mild exposure to DME vapours causes eye, nose, and throat irritation. DME's overexposure can cause headaches, dizziness, light-headedness, and even unconsciousness. Direct skin contact with liquid DME may cause serious frostbite (https://nj.gov/health/eoh/rtkweb/documents/fs/0758.pdf). However, many studies have concluded that DME is a non-carcinogen (MacFarlane 1965). Long-duration underground parking of DME fuelled vehicles should be avoided because DME vapours can replace the oxygen in the parking space. This may cause suffocation to humans and animals. DME is flammable, and there is a risk of explosion if an open flame is thrown on the ground, where DME vapours may be accumulated. The health effects of DME are listed in Table 3.1.

Well-to-wheel SO_2 and NO_x emissions from DME-fuelled engines are lower than mineral diesel. Particulate emissions are also lower in the case of DME. SO_2 and

Table 3.1 Health effects of DME (MacFarlane 1965)

Item	Health effects on humans
Principal routes of exposure	Inhalation, eye contact, skin contact
Acute toxicity	None
Inhalation	May cause central nervous system depression with nausea, headache, dizziness, vomiting and incoordination
Eyes	May irritate. Contact with liquid may cause frostbite
Skin	May irritate. Contact with liquid may cause frostbite
Skin absorption hazard	No known hazard in contact with skin
Ingestion	Not an expected route of exposure
Chronic effects	No known effect based on the information available
Aggravate medical conditions	Skin disorders, effect on the central nervous system, respiratory disorders

particulates are responsible for winter fog. Therefore, DME's winter and summer smog potential is lower than mineral diesel. Emissions of benzene, toluene, xylene, and PAHs are lower for DME because a molecule of DME contains only two carbon atoms connected by oxygen. Soil contamination is unlikely to happen with DME because DME is stored in a pressurised vessel and remains in the vapour phase above −25 °C. DME leak will likely vaporise into the atmosphere rather than contaminate soil or water (MacFarlane 1965). DME has lower reactivity in photochemical reactions. Therefore, DME has significantly lower ozone-forming reactivity than all organic compounds explored for fuel usage (Sorenson 2001; Bowman and Seinfeld 1995). DME does not form formaldehyde and other oxygenated compounds in the photochemical reactions in the environment (Japar et al. 1990). Formaldehyde emissions are higher in DME combustion than in mineral diesel. Formaldehyde is a carcinogenic, poisonous, and allergic compound (Tripathi et al. 2022). Diesel oxygen catalysts (DOC) used in DME-fuelled engines can reduce formaldehyde levels to zero.

3.7 Properties of DME

DME is the best alternative to diesel, considering its superior physicochemical properties over diesel (Table 3.2). Low autoignition temperature and high CN of DME make it an excellent replacement to diesel in CI engines. Low vapour pressure of DME facilitates better fuel-air mixing, thus, increasing combustion efficiency and reducing HC and CO emissions than baseline diesel. However, the low kinematic viscosity of DME causes wear and leakage in FIE (Table 3.2).

Table 3.2 Properties of DME and diesel (Tripathi et al. 2022)

Properties	DME	Diesel
Chemical Structure	CH_3OCH_3	C_8–C_{25}
Molecular Weight (g/mol)	46.07	190–220
Density (l) (kg/m^3) @25 °C	668	856
Density (g) (kg/m^3) @25 °C	1.918	–
Flammability range in air (% v/v)	(3.4–18)	(1–6)
Boiling point (°C)	−23.6	180–370
Autoignition temperature (°C)	350	250
Cetane number (CN)	55–62	40–55
Octane number (ON)	–	–
Lower heating value (LHV) (MJ/kg)	27.6–28.8	42.5–43.2
Latent heat of vaporization (kJ/kg)	460–470	270
Stoichiometric ratio	8.9	14.3
Oxygen (% w/w)	34.8	0
Flash point (°C)	−41	>55
Kinematic viscosity (l) cSt @30 °C	<0.1	3.0–7.5
Ignition energy (mJ)	0.29	20
Vapour pressure (kPa) @20 °C	516.76	1–10

3.8 Advantages and Challenges of DME

DME is gaining much interest among researchers as an ultra-clean, renewable CI engine fuel. DME has better atomisation characteristics, high CN, oxygen content (34.8% w/w), latent heat of vaporisation, and low self-ignition temperature (Kanta et al. 2022) (Mehra and Agarwal 2022). The ignition delay difference between diesel and DME is ~1.3–2.3° CA (Park and Lee 2013). During combustion polycyclic aromatic hydrocarbons (PAHs) are formed in the combustion chamber. DME is a non-toxic fuel that degrades quickly in the troposphere. The C–O bond is present in DME, and due to its lower bond energy than the C–H bond, it breaks more easily. This results in the superior ability of the pyrolysis mechanism to initiate chain reactions at low temperatures, leading to auto-ignition at lower temperatures for DME (Park and Lee 2014; Agarwal et al. 2017). DME can utilise infrastructure designed for propane storage and transport (Morsy et al. 2006). Due to the superior evaporative characteristics of DME spray, the wall-wetting effect reduces in DME-fueled engines.

DME also has some challenges, such as ultra-low viscosity, low self-lubrication properties, high vapour pressure, low critical point, and so on, all of which make it difficult for conventional FIS (Agarwal et al. 2017). DME has a lower calorific value and bulk modulus, one-third of mineral diesel. We can’t utilise the same sealing materials for DME as we do for traditional diesel FIE. The compatibility of DME is good with most metals and alloys but not with polymeric compounds (Kumar and Agarwal 2021). Numerous parts of the FIE leak due to the ultra-low viscosity, necessitating the employment of different sealing materials. Many components corrode due to a lack of self-lubrication properties. The viscosity of DME-diesel blended fuels containing 25% DME is lower than ASTM specification for diesel. These difficulties can be addressed by adding viscosity improvers and lubricity additives to DME. However, this will not be enough to bring DME's viscosity up to standard fuels. Due to its low viscosity, DME does not form a hydrodynamic fluid layer, which causes metal-to-metal contact and wear. Various studies have shown that when DME content is greater than 50% in any blended or dual-fuel operation, none of the additives or fuels provides appropriate viscosity, resulting in the corrosion of many components, such as the plunger of a high-pressure pump (Chapman et al. 2004). This issue can be partially handled by building a DME-dedicated FIE rather than adding different additives to DME to make it compatible with traditional diesel-dedicated FIEs. DME has a low modulus of elasticity, making it five times more compressible than diesel. This results in greater compression effort for the fuel pump to pressurise the DME (Park and Lee 2014; Arcoumanis et al. 2008).

DME has a low enthalpy of combustion than diesel. Lower spray penetration and faster DME ignition lead to inadequate air entrainment in the DME spray. This might cause deteriorated combustion, particularly at high loads and speeds, leading to significant CO emissions and high fuel consumption in DI DME-fueled CI engines. The lower acoustical velocity caused by DME's higher compressibility also causes a longer injection delay than diesel fuel (Huang et al. 2009). Sulphur content in DME is zero. However, SO_2 emissions from DME fuelled engines are higher than diesel. DME with a high concentration (500 ppm) of fatty acid-based lubricant emits more SO_2 than DME with a low concentration (50 ppm) of fatty acid-based lubricants (Oguma et al. 2005). Although, these fatty acids and ester-based lubricants have no sulphur content. Engine oil seems to be the source of SO_2. The chances of DME leakage into the high-pressure fuel pump are large due to the low viscosity of DME. The mechanism for collecting the gaseous DME from the gallery of plunger supplies it back to the fuel return line after liquifying it. As a result, the leaking DME collecting mechanism might have collected the gaseous DME and lubricating oil to lubricate the HP fuel pump. Therefore, SO_2 emissions generally increase in a DME engine (Oguma et al. 2005).

3.9 Engine Hardware Modifications for DME Adaptation

Hardware modifications are required in the existing diesel-fueled CI engines to make them compatible with DME fueling. Significant changes in the FIE and sealing materials, along with a change in the material, are required.

DME Storage and Handling System: Vapour pressure of DME varies from 4 to 10 bars (abs) during normal weather conditions in India (Table 3.3). DME storage tank and its various components, such as valves, must withstand pressure as high as 10 bar. DME generates more vapours than diesel in the FIE (Sorenson 2001).

DME is a gas at NTP due to its high vapour pressure. DME becomes liquid at ~6 bar absolute pressure at normal temperature. Table 3.3 shows DME's vapour pressures, corresponding temperatures, and other thermodynamic properties.

Unlike diesel, DME must be pressurised using either a low-pressure (LP) pump or compressed nitrogen. It ensures DME supply in the liquid phase and avoids vapour lock in the fuel lines. DME has high compressibility since it is near the critical state (Sorenson 2001). Due to the high compressibility of DME, the plunger of high-pressure (HP) pump would not be able to generate the required pressure, and most of its energy would be wasted in compressing DME. Hence, a high-pressure DME supply is required at the inlet of the HP pump to avoid this problem. Fuel heating may occur when engine runs at high temperatures, increasing compressibility and a drop in fuel density. This creates difficulties in maintaining a full engine load due to the lack of fuel supply. Therefore, DME-powered diesel engines' fuel cooling or temperature management is necessary (Sorenson 2001). This arrangement will ensure the supply of liquid DME. Another alternative is to supply the vapourised DME back into the DME storage tank. Then, DME will be compressed and liquefied again by the LP pump before supplying to the feed pump.

Material Compatibility: Replacement of various sealing parts of FIS with parts made from DME-compatible materials is paramount to its widespread usage. Otherwise, its use in existing engines causes engine parts to wear and fuel leakage. Kass and Daw (2016) performed Hansen solubility analysis for various materials with DME, diesel and its blends. Styrene butadiene rubber (SBR) and nitrile butadiene rubber (NBR) showed similar solubility potential for DME, diesel and blends of both fuels. Therefore, no degradation of these materials is expected. However, fluorocarbon became more incompatible with DME upon increasing the DME concentration in diesel-DME blends. Polyester resins were highly incompatible with both fuels and showed high solubility with diesel and DME. Table 3.4 shows the compatibility of different materials with DME.

The compatibility of DME is good with metals and alloys because DME does not decompose into acids (https://afdc.energy.gov/files/pdfs/3608.pdf). The most common hose and seal material are NBR. Three manufacturers considered NBR a DME-compatible material, but Allorings did not consider it DME-compatible.

Lubricity Dosing Arrangement: The kinematic viscosity of DME is around one-tenth of diesel. Diesel acts as a lubricant for the FIE. However, DME causes the wear of FIE components due to the lack of viscosity and self-lubricating characteristics. Adding lubricity and viscosity-improving additives to the DME is necessary to avoid leakage and wear of engine and FIE components. Hansen et al. (2000) observed that the "Lubrizol LZ539N" lubricity additive has the best wear-reducing characteristics. DME does not have a recognisable odour. Therefore, odour additives must be added to DME to detect any leakage and to minimise the chances of fatal accidents. Hansen et al. (2000) used Ethyl mercaptan as an odour improver in DME due to its almost similar boiling point to DME and better blending characteristics with DME. A 1000 ppm lubricity additive (Lubrizol LZ539N) and 20 ppm of odour additive Ethyl mercaptan were initially added to DME to avoid the adverse effects on exhaust emissions. Unlike DME, lubricity and odour additives are in the liquid phase during

Table 3.3 Thermodynamic properties of DME (Teng et al. 2001)

Pressure (abs) (bar)	Temperature (°C)	Density (kg/m^3)		Enthalpy (kJ/kg)		Latent heat (kJ/kg)	Entropy (kJ/kg K)		Surface tension (N/m)
		Liquid	Vapour	Liquid	Vapour		Liquid	Vapour	
1.0	−25.0	723.42	2.327	98.513	566.03	467.52	0.881	2.766	0.01778
1.013	−24.8	723.16	2.345	98.963	566.25	467.29	0.884	2.767	0.01776
2.0	−8.28	701.33	4.443	137.48	584.97	447.50	1.152	2.842	0.01551
3.0	2.81	686.00	6.522	164.07	597.42	433.36	1.319	2.891	0.01402
4.0	11.3	673.78	8.581	184.52	606.46	421.95	1.443	2.927	0.01288
5.0	18.4	663.39	10.64	201.21	613.36	412.14	1.541	2.956	0.01194
6.0	24.4	654.21	12.69	215.33	618.74	403.40	1.624	2.980	0.01114
7.0	29.7	645.90	14.75	228.80	624.22	395.42	1.695	3.001	0.01044
8.0	34.5	638.24	16.83	241.11	629.13	388.02	1.758	3.020	0.00981
9.0	38.9	631.09	18.92	252.30	633.36	381.06	1.814	3.036	0.00924
10.0	42.9	624.35	21.03	262.61	637.06	374.45	1.865	3.051	0.00871
11.0	46.6	617.95	23.16	272.20	640.33	368.13	1.912	3.064	0.00823
12.0	50.1	611.82	25.30	281.20	643.24	362.05	1.955	3.076	0.00778
13.0	53.4	605.92	27.48	289.69	645.85	356.16	1.996	3.087	0.00736
14.0	56.5	600.23	29.67	297.76	648.20	350.44	2.033	3.097	0.00697
15.0	59.5	594.70	31.90	305.46	650.33	344.86	2.069	3.106	0.00660
16.0	62.3	589.31	34.15	312.85	652.25	339.40	2.102	3.114	0.00625
17.0	65.0	584.04	36.43	319.98	654.01	334.04	2.134	3.122	0.00591
18.0	67.6	578.89	38.74	326.86	655.62	328.75	2.164	3.130	0.00560
19.0	70.1	573.82	41.09	333.55	657.08	323.53	2.193	3.136	0.00530

(continued)

Table 3.3 (continued)

Pressure (abs) (bar)	Temperature (°C)	Density (kg/m^3)		Enthalpy (kJ/kg)		Latent heat (kJ/kg)	Entropy (kJ/kg K)		Surface tension (N/m)
		Liquid	Vapour	Liquid	Vapour		Liquid	Vapour	
20.0	72.5	568.83	43.47	340.06	658.43	318.37	2.221	3.143	0.00501
21.0	74.8	563.90	45.88	346.41	659.66	313.25	2.248	3.148	0.00474
22.0	77.0	559.03	48.33	352.63	660.79	308.16	2.273	3.154	0.00447
23.0	79.2	554.20	50.82	358.73	661.83	303.09	2.298	3.159	0.00422
24.0	81.3	549.40	53.35	364.74	662.78	298.04	2.322	3.163	0.00398
25.0	83.3	544.63	55.92	370.67	663.66	292.99	2.345	3.167	0.00375
26.0	85.3	539.88	58.53	376.53	664.46	287.93	2.368	3.171	0.00353
27.0	87.3	534.75	61.18	382.34	665.20	282.86	2.391	3.176	0.00331
28.0	89.2	528.41	63.88	388.11	665.88	277.77	2.414	3.181	0.00306
29.0	91.0	522.77	66.63	393.85	666.50	272.65	2.436	3.185	0.00285
30.0	92.8	517.48	69.43	399.58	667.06	267.48	2.457	3.188	0.00265
31.0	94.6	512.33	72.28	405.31	667.58	262.27	2.478	3.191	0.00247
32.0	96.3	507.19	75.18	411.05	668.05	257.00	2.498	3.194	0.00229
33.0	98.0	501.97	78.13	416.82	668.47	251.65	2.518	3.196	0.00212
34.0	99.6	496.63	81.14	422.63	668.86	246.23	2.538	3.198	0.00196
35.0	101.2	491.17	84.21	428.49	669.20	240.71	2.557	3.200	0.00180
36.0	102.8	485.59	87.35	434.43	669.51	235.08	2.577	3.202	0.00165
37.0	104.4	479.88	90.54	438.40	667.73	229.33	2.596	3.204	0.00151
38.0	105.9	474.06	93.80	443.60	667.04	223.44	2.616	3.205	0.00138

(continued)

Table 3.3 (continued)

Pressure (abs) (bar)	Temperature (°C)	Density (kg/m^3)		Enthalpy (kJ/kg)		Latent heat (kJ/kg)	Entropy (kJ/kg K)		Surface tension (N/m)
		Liquid	Vapour	Liquid	Vapour		Liquid	Vapour	
39.0	107.4	468.11	98.31	449.50	666.88	217.38	2.635	3.206	0.00123
40.0	108.9	462.04	102.80	455.86	667.00	211.14	2.654	3.207	0.00110
41.0	110.3	455.82	107.20	462.46	667.15	204.69	2.674	3.208	0.00097
42.0	111.7	449.40	111.62	469.14	667.13	197.98	2.693	3.207	0.00086
43.0	113.2	442.75	116.19	475.74	666.74	190.99	2.712	3.206	0.00075
44.0	114.5	435.78	121.05	482.14	665.80	183.66	2.731	3.205	0.00065
45.0	115.9	428.41	126.39	488.23	664.15	175.93	2.750	3.202	0.00055
46.0	117.2	420.52	132.41	493.96	661.66	167.70	2.769	3.198	0.00045
47.0	118.6	411.96	139.38	499.32	658.17	158.86	2.788	3.194	0.00036
48.0	119.9	402.55	147.61	504.34	653.59	149.25	2.808	3.188	0.00028
49.0	121.2	392.02	157.56	509.18	647.79	138.61	2.829	3.181	0.00020
50.0	122.4	380.01	169.84	514.11	640.68	126.57	2.852	3.172	0.00013
51.0	123.7	365.90	185.38	519.77	632.16	112.39	2.878	3.162	0.00007
52.0	124.9	348.43	205.60	527.61	622.15	94.54	2.912	3.150	0.00003
53.0	126.1	323.66	232.88	542.49	610.58	68.08	2.965	3.136	0.000004
53.7	127.0	258.51	258.51	601.46	601.46	0.000	3.125	3.125	0.00000

Table 3.4 Material compatibility of different sealing materials with DME (Kass and Daw 2016)

Material class	Manufacturer				
	Mykin	Geotech	Hargraves	Allorings	Parr
Elastomers					
NBR&SBR	Satisfactory	Acceptable		Not recommended	Acceptable
Neoprene	Doubtful	Unsatisfactory			
Fluorocarbon	Fair		Acceptable	Not recommended	Acceptable
Fluorosilicone			Acceptable	Recommended	Acceptable
Silicone				Recommended	Acceptable
Plastics					
PTFE (Teflon)		Resistant			

NTP conditions. Thus, DME must be in the liquid phase for better mixing of DME and additives. DME should be stored at a higher pressure than its vapour pressure. Fuel must be circulated continuously in the fuel tank to avoid the settling down of additives after prolonged dosing. DME is supplied to the consumption tank from the main DME storage tank using a feed pump. Odour and lubrication additives are injected into the DME fuel line using an additive dosing pump and are mixed with the DME flowing in the fuel lines. A circulation pump is installed after the dosing pump to help with continuous fuel circulation, preventing improper mixing.

3.10 DME Fuelled Vehicle Development Projects

3.10.1 DME FIE Development for Heavy-Duty Trucks

DME is easier to liquefy than other fuels, such as CNG and Hydrogen. Therefore, liquid DME can easily be stored in the vehicle. The DME engine for a 20-ton GVW truck was developed under the Ministry of Land, Infrastructure and Transport of Japan (Tsuchiya and Sato 2006). In the DME FIE, the diameter of the nozzle hole of the fuel injector was increased to supply a higher amount of DME. A feed pump was used to compress the DME to moderate the pressure. DME was provided from the feed pump to the modified BOSCH HP pump. HP pump compressed the DME to a pressure higher than the fuel injector's nozzle opening pressure. DME was injected into the combustion chamber by the fuel injector, and some amount of DME was allowed to flow to the DME fuel tank via fuel return lines. Since the DME combustion is smoke-free, heavy EGR was introduced to reduce NO_x emissions. The exhaust gas was taken from the exhaust manifold upstream of the turbine and delivered to the upstream compressor assembly. NO_x emissions were reduced to one-fourth of Japan's long-term emission regulation limit (2005).

3.10.2 DME FIE Development for City Bus

The main hurdles for DME-dedicated FIE development are high vapour pressure, compressibility, and low viscosity of DME. The common rail type system is best suited to handle all these features of DME to develop dedicated FIE for city buses (Hansen et al. 2000). The electrical control unit (ECU) monitors the DME distribution to system. The fuel level is checked in both tanks at the time of the ignition event. DME is allowed to flow from the fuel tank with a large quantity of DME to the tank with a lower quantity to ensure even fuel distribution in both tanks. DME is pumped with a pressure of 10 bar higher than the vapour pressure. The purge system of the purge tank operates on the compressed air from the brake system of the bus. A separate fuel line connects the purge tank to the FIE. A level indicator in the purge tank calculates the amount of liquid DME. If the DME quantity is more than 15 L, this will be indicated on the driver's interface. If the pressure inside the purge tank reaches higher than the permissible limit, the pneumatic control unit activates the purge compressor. The compressor compresses the gaseous DME and supplies it to the fuel tank until the pressure inside the purge tank reaches the permissible limit (Hansen et al. 2000). Arrangement for cooling of circulating DME was necessary. A separate circuit was provided to handle the engine's water-to-air charge-air cooling. The water temperature is adequate for DME cooling. Afterwards, the city bus was operated on the DME. Significantly lower PM and NO_x emissions were observed while operating the city bus on DME. HC and CO emissions were reduced while using an oxidation catalytic converter.

3.10.3 DME FIE Development for Engines

The FIE system customised for DME was tested in the engine. With the changed SoI timing of DME and unaltered SoI timing of diesel, BTE was slightly greater for diesel than DME at lower loads. The BTE of diesel and DME were comparable at medium-to-high loads (Oguma et al. 2004). EGT was higher for diesel than DME at all engine operating conditions. Due to the lower LHV of DME, lesser energy was released during combustion than diesel. Therefore, lower in-cylinder temperature and EGT were observed for DME. Huang et al. (2009) reported the lowest BSFC for both fuels in the speed range, where maximum torque was obtained. As engine load increased, the BSFC of diesel and DME reduced. BSFC for DME was lower than mineral diesel at lower loads but comparable at higher loads. The LHV of DME is ~2/3rd that of mineral diesel. As a result, each cycle requires 1.9 times the diesel volume in the combustion chamber to maintain the same diesel engine power output from DME fuelling. This led to a long fuel injection duration and large DME consumption at high engine speeds. Therefore, the BSFC of DME increased drastically and became equivalent to the 1.9 times the BSFC of diesel at high engine loads.

3.11 Combustion Characteristics of DME

The engine's performance and exhaust emissions depend on combustion characteristics. Therefore, improving the in-cylinder combustion can improve engine performance and reduce the emissions. This section compared combustion parameters such as in-cylinder pressure, rate of pressure rise (RoPR), heat release rate (HRR), cumulative heat release (CHR), indicated mean effective pressure (IMEP), ignition delay and combustion phasing for DME and diesel engines.

3.11.1 In-Cylinder Pressure and RoPR

Lower peak pressure of the DME-fueled engine was observed than mineral diesel for the same fuel injection volume since DME has a lower calorific value (28.43 MJ/kg) than diesel (42.5 MJ/kg) (Fig. 3.13) (Park and Lee 2014; Kim et al. 2007a). More DME must be injected to improve the combustion to match the diesel energy input (Park and Lee 2014). Many studies have reported a lower peak in-cylinder pressure for DME than baseline diesel (Huang et al. 2009; Longbao et al. 1999; Sorenson and Mikkelsen 1995). Huang et al. (2009) reported that the DME's SoI delay was substantially longer than the reduction in ignition delay; thus, the SoC of DME retarded compared to diesel. Hence, the rise of in-cylinder pressure and $RoPR_{max}$ is also retarded for DME than diesel. SoI of DME was delayed due to the requirement of high compression energy for DME HP pump than diesel. Engine noise was also low for DME combustion due to low peak in-cylinder pressure and $RoPR_{max}$ (Sorenson and Mikkelsen 1995; Christensen et al. 1997; Huang et al. 1999). The effects of changes in SoI timings and EGR rates on the in-cylinder pressure were also reported by researchers.

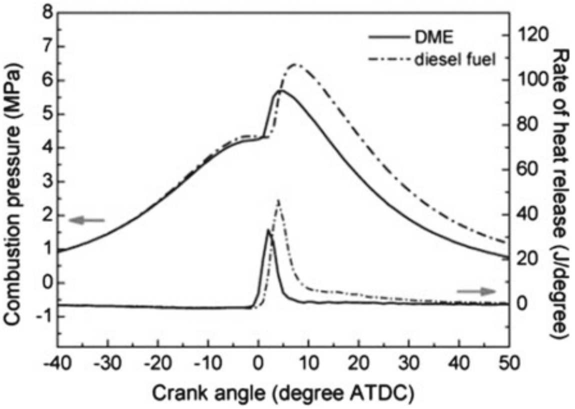


Fig. 3.13 In-cylinder pressure and heat release rate variations of DME and baseline diesel at SoI timing of 6° bTDC (Kim et al. 2007a)

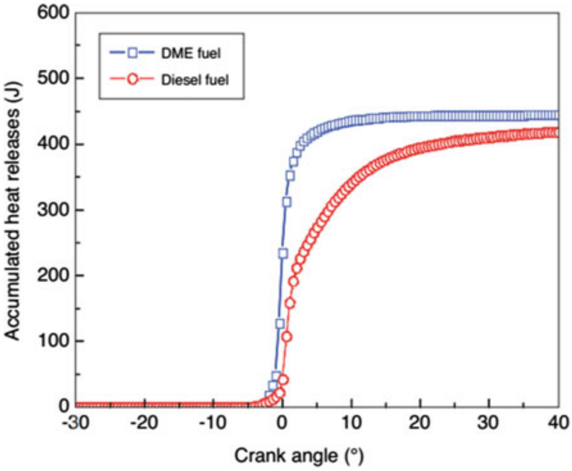
Kim et al. (2008b) compared in-cylinder pressures at 8° bTDC and 2° bTDC SoI timings for DME and diesel. Since DME spray ignited more quickly than other fuels, DME-fueled engines exhibited a higher maximum in-cylinder pressure at 8° bTDC SoI timing. For this, increased chemical and thermal effects, heat capacity and dilution effects were responsible since they lengthened the ignition delay and enabled superior charge mixing. At the retarded injection timing of 2° bTDC, a higher premixed spike was observed than the injection timing of 8° bTDC for DME. Retarded SoI timing of fuel increased the ignition delay, increasing the accumulated energy between SoI and SoC. Therefore, a higher premixed spike was observed at 2° bTDC SoI timing. Yoon et al. (2013) showed that a high EGR rate lowered the in-cylinder temperatures and pressures during the expansion stroke.

3.11.2 HRR and CHR

DME has a lower HRR than mineral diesel in the premixed combustion phase. Due to its low ignition delay, a small DME quantity accumulates in the combustion chamber before the SoC. This results in lesser combustion noise and lower NO_x emissions in DME combustion than diesel. The HRR_{max} in the diffusion combustion phase was also lower for DME than diesel due to its rapid mixing and high diffusivity (Longbao et al. 1999). At the same fuel SoI timing, the fuel injection delay was longer for DME due to the high compression work requirement than diesel. Therefore, the SoC and HRR of DME were significantly retarded than diesel (Huang et al. 1999). Huang et al. (2009) also reported a lower peak of HRR for DME than diesel. The rise in HRR was retarded for DME than diesel.

DME burns faster because of its short ignition delay, resulting in fast and increased heat release. DME produced more heat than mineral diesel at the same injection timing, same fuel energy input, and fixed engine speed. Premixed combustion affects heat release, which is critical for CHR in DME combustion of a homogeneous charge. Kim et al. (2008b) analysed the HRR of mineral diesel and DME at various SoI timings. HRR_{max} was lower and advanced for DME at 8° bTDC SoI timing due to decreased energy supply from DME than diesel. Once SoI was retarded to 2° bTDC, the HRR_{max} for DME combustion was greater than diesel. Retarded SoI timing of DME increased the ignition delay, increasing the accumulated energy between the SoI and SoC. The temperature of the charge reduced rapidly, and the reaction rate slowed when the ignition was delayed beyond the TDC, lowering the peak HRR of diesel combustion. Kim et al. (2008a) compared three injection scenarios: a single injection near TDC, an early single injection for PCCI combustion, and a dual injection for partially premixed charge compression ignition (PPCCI) combustion. The dual injection includes one early injection followed by a late injection after the TDC. The overall mass of fuel injection was the same for all three circumstances to keep the same equivalence ratio. The traditional single injection caused dispersed combustion and a single peak in the HRR curve. There were two peaks in the HRR curve for PCCI combustion. Low-temperature combustion caused the initial peak,

Fig. 3.14 CHR of diesel and DME (Kim et al. 2012)



followed by a short igniting delay due to the fuel's negative temperature coefficient behaviour. A premixed high-temperature reaction was responsible for the second large peak. When the equivalence ratio increased, both LTR and HTR advanced. Two peaks were attributed to initial early injection, like PCCI combustion, while the third peak was due to diffusion combustion of late second fuel injection, similar to PCCI combustion. The initial two peaks of PPCCI combustion were lower than the peaks of PCCI combustion due to a lower amount of fuel injected (fuel injection is split in two parts in PPCCI combustion).

DME had a larger injected fuel mass than diesel, which resulted in a higher CHR for a given calorific value (Fig. 3.14). CHR of DME and diesel became stable after around 5° and 30° aTDC, respectively. DME exhibited faster atomisation and evaporation characteristics than diesel. DME rapidly mixes with the surrounding air and burns faster than diesel. This resulted in DME's earlier end of combustion than mineral diesel (Kim et al. 2012). Hence, the CHR of DME became stable at 25° CA before the diesel CHR.

3.11.3 IMEP

Kim et al. (2008b) detected a reduction in IMEP at advanced SoI timings due to increased negative effort during the compression stroke. A higher IMEP means greater combustion efficiency. Despite the fast ignition of DME, it has a greater IMEP than mineral diesel over practically the entire range of injection duration (Fig. 3.15).

DME combustion creates a non-luminous flame, producing lower radiation and cooling losses than diesel. DME combustion efficiency is also higher than diesel. These are some of the possible reasons for higher IMEP during DME combustion. PCCI combustion significantly increases IMEP than conventional CI combustion

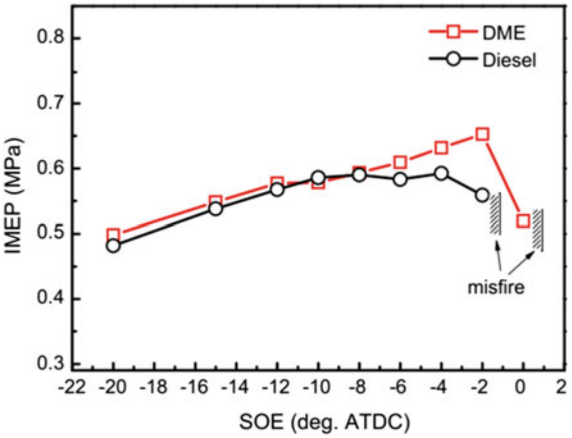


Fig. 3.15 IMEP of diesel and DME at varying start of energizing and constant energy input (Park and Lee 2013)

(Kim et al. 2008a). Yoon et al. (2013) reported that due to long ignition delay and combustion duration, the introduction of EGR increased the IMEP because the heat of combustion was released between the end of the compression stroke and the beginning of expansion stroke.

3.11.4 Ignition Delay and Combustion Phasing

The ignition delay of DME is significantly lesser than mineral diesel (Fig. 3.6) (Park and Lee 2014; Kim et al. 2008b; Huang et al. 1999, 2009). High cetane number, superior spray atomisation characteristics and low autoignition temperature are responsible for DME's short ignition delay (Longbao et al. 1999). Ignition delay strongly depends on temperature. Lower temperature increases the ignition delay (Park and Lee 2014). However, DME's fuel injection delay is higher than diesel due to its higher compressibility. Kass and Daw (2016) reported that the injection delay of DME decreased more compared to diesel with increasing load. The ignition delay of DME was reduced more than diesel with increasing engine load. The high compressibility of DME was responsible for the difference in acoustics velocity and injection delay between both test fuels (Huang et al. 2009).

Ignition delay of DME can be expressed as;

$$\tau_{\mathbf{id}} = \mathbf{0.022P^{-0.316}e^{(4206/T)}}$$

Where; τ_{id} = ignition delay (ms), P = in-cylinder pressure (bar), T = in-cylinder gas temperature (K) (Park and Lee 2014).

3.11.5 Fuel Line Pressure, Injection Duration and Injection Delay

Christensen et al. (1997) reported that the peak fuel line pressure ($P_{\text{line\_max}}$) of DME was significantly lower than diesel. At the start of DME's fuel injection, the pressure rise was lower than diesel. The plunger of the HP pump displaces the fuel through the nozzle of the fuel injector. A greater amount of compression work of the HP pump was used to compress the DME than diesel. Therefore, DME's pressure built up for the same plunger movement was lower. The study also reported lower fuel injection velocity and longer fuel injection duration of DME than baseline diesel. Fuel injection duration increased upon increasing the plunger stroke. A large amount of DME was injected due to its low calorific value to maintain the same power output as the diesel engine. Therefore, an increase in plunger stroke increased the fuel injection duration of DME compared to mineral diesel (Huang et al. 1999). $P_{\text{line\_max}}$ and RoPR of DME were substantially lower than diesel under identical fuel supply advance angle and load (Huang et al. 2009). DME's high compressibility and low nozzle opening pressure are perhaps the reason for low fuel line pressure. The speed at which the sound wave moves through a medium is called its acoustic velocity. Acoustics velocity increased in DME with increasing engine load. Because of low acoustic velocity, the pressure wave takes longer to propagate in DME than in diesel. Therefore, the DME injection delay is longer than mineral diesel (Huang et al. 1999). Fuel injection duration of DME is lesser as compared to diesel because lower kinetic viscosity of DME led to the rapid flow of fuel through the injector nozzle, therefore substantially higher flow rate as compared to diesel (Kim et al. 2007a).

3.12 Emission Characteristics of DME

There is a growing concern about tailpipe emissions from automobiles due to their adverse health and environmental effects. Therefore, governments impose strict emission legislation on the road transport industry. This section compares the formation and reduction techniques of various regulated, unregulated, particulates and trace metal emissions from diesel and DME engines.

3.12.1 Regulated Emissions

Tailpipe emissions regulated CO and HC emissions from gasoline engines in 1959 in California for the first time. IC engine emissions are now regulated in many nations worldwide. NO_x, CO, HC and PM are the regulated emissions. This section compares the regulated emissions from diesel and DME-fueled engines.

NOx Emissions: Combustion temperature, presence of oxygen, and residence time at peak combustion temperature are the major parameters influencing NO$_x$ production, according to the Zeldovian diesel-fueled engines due to itch mechanism (Zhao et al. 2014; Zhu et al. 2012). NO$_x$ emissions increase where excess oxygen and high peak temperature are available in the combustion chamber. Many studies on NO$_x$ emissions from DME-fueled CI engines are inconsistent. Some studies claim that DME generates lower NO$_x$ than diesel-fueled engines due to its high CN, low heating value, and high latent heat capacity (Zhu et al. 2012; Mukherjee et al. 2022). In addition, retarded SoI timing of DME can further reduce the NO$_x$ emissions upon DME combustion (Fig. 3.16). Under the same diffusion condition, DME combustion produces lower NO$_x$ than diesel. In contrast, NO$_x$ emissions increase for DME under the same HRR condition (Park and Lee 2014). Since the release of free oxygen from DME is limited, the influence of intermolecular oxygen on NO$_x$ emissions is insignificant.

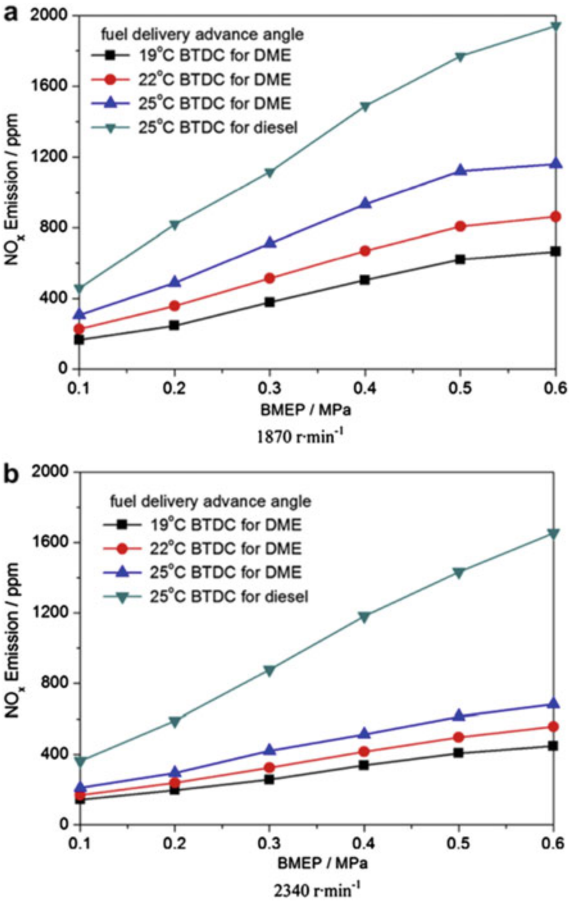


Fig. 3.16 NO$_x$ emissions from diesel and DME at varying engine speeds and SoI timings (Zhu et al. 2012)

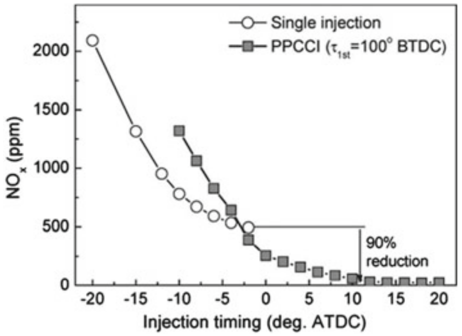


Fig. 3.17 Effect of single fuel injection and PPCCI strategies on NO_x emissions from DME fuelled engine (Kim et al. 2008a)

In contrast, many studies reported that DME-fuelled engines emitted higher NO_x than diesel-fuelled engines (Kim et al. 2007a; Thomas et al. 2014). Faster ignition and combustion of DME enhanced the in-cylinder temperature, raising NO_x emissions more than diesel (Park and Lee 2013). DME has a quick combustion response due to its high CN and excellent spray atomisation characteristics. As a result, DME has a higher HRR and HRR_{max} than diesel. The fuel-bound oxygen of DME also acts as an oxidiser, speeding up the NO_x formation reactions and raising the peak combustion temperature. As a result, the DME engines emit high NO_x emissions. Kim et al. (2007b) also showed high NO_x emissions from DME-fueled engines across the selected SoI timings because the charge temperature increased in the combustion chamber due to faster HRR caused by rapid combustion. NO_x emissions increased at 2° bTDC SoI timing. NO_x emission further increased at advanced SoI timing of 4° bTDC. Two popular technologies, low-temperature combustion (LTC) and EGR, can reduce the NO_x emissions from DME-fueled engines to the same or even lower levels than diesel engines. For LTC approaches like PCCI, DME-fueled engines emitted low NO_x (Fig. 3.17) (Kim et al. 2008a). Exhaust gas after-treatment methods include urea selective catalytic reduction (SCR), lean NO_x traps (LNT), HC-SCR, and the combination of EGR and catalysts are also effective in limiting NO_x emissions (Park and Lee 2014).

When the fuel injection in a CI engine is advanced enough, combustion occurs in a lean, premixed mode, which produces extremely low NO_x while simultaneously increasing HC emissions and fuel consumption. PPCCI was used to obtain the advantages of PCCI combustion while removing its drawbacks. PCCI is combined with conventional CI combustion in the PPCCI combustion, wherein an early pilot injection is employed to premix a portion of fuel, and a second injection occurs after the TDC.

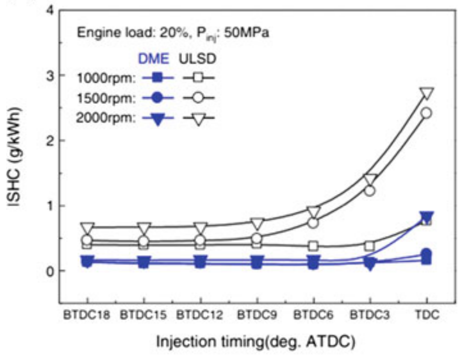
HC and CO Emissions: Unburnt HC and CO emissions are the intermediate compounds formed during the combustion of complex hydrocarbons in favourable conditions. They are further oxidised to CO_2 and H_2O. High combustion temperatures accelerate the oxidation of HC and CO, lowering their concentration in the exhaust. The chain termination of the hydrocarbon oxidation process causes HC emissions (Jang et al. 2009; Oh et al. 2010). Under fuel-rich and imperfect fuel-air mixing conditions, HC forms from partial or unburned fuel. Many studies reported that DME-fueled engines emitt significantly less HC than diesel-fueled engines (Fig. 3.18).

DME has superior spray atomization, evaporation characteristics, and a shorter ignition delay, so it isn't easy to generate over-rich regions due to short mixing time. DME's fuel bound oxygen avoids fuel-rich zones and lowers the HC emissions (Park and Lee 2014). DME spray penetration is lower than mineral diesel. Hence, DME is less susceptible to the wall-wetting effect. This also results in lower HC emissions from DME-fueled engines since diesel spray is more likely to impinge upon the cylinder walls, resulting in incomplete combustion due to the wall heat transfer and a drastic reduction in the local in-cylinder temperature inhibiting HC oxidation. Park and Lee (2013), Kim et al. (2008b) and Youn et al. (2011) reported that DME-fueled engines emitted lesser HC and CO than diesel-fueled engines (Fig. 3.18).

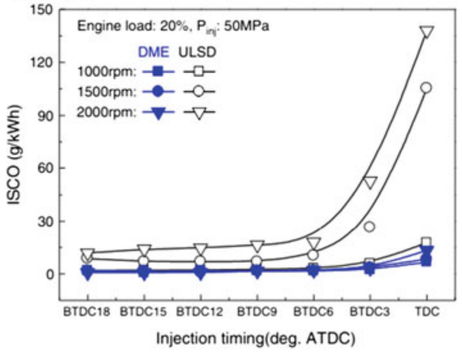
PCCI combustion requires earlier fuel injection than a conventional CI engine. If the piston shape is not modified, using PCCI combustion in a CI engine fuelled by DME increases HC and CO emissions. Low in-cylinder pressure can increase spray penetration and fuel deposition on the cylinder walls (Kim et al. 2008a). The PPCCI combustion is a hybrid of PCCI and conventional combustion that reduces NO_x, CO and HC emissions from DME engines at the same time. Kim et al. (2007b) reported

Fig. 3.18 ISHC and ISCO emissions from diesel and DME at varying fuel injection timings and engine speeds (Youn et al. 2011)

(a) ISHC



(b) ISCO



that PPCCI combustion generates higher HC and CO emissions than conventional single-injection combustion. If the main injection is delayed after the TDC, HC emissions rise higher than in the single injection case for all pilot injection timings. HC emissions increased for main injection timing before 20º bTDC with advanced pilot injection. Despite the dilution effect of EGR, Yoon et al. (2013) found that the increased oxygen level and reduced C–H ratio caused complete combustion, reducing the unburned CO and HC emissions. However, for all the test cases and EGR rates, CO and HC emissions rose at advanced SoI timing before 25° bTDC. This causes a significant fuel quantity to be trapped in crevices during prolonged ignition delay, as well as an increased risk of unburned HC emissions due to the crevice effect and wall-wetting at high EGR rates with earlier SoI timings. High EGR rates may reduce combustion temperature, increasing HC emissions. Furthermore, by lowering the combustion temperatures, CO–CO_2 conversion slows down (Thomas et al. 2014). Incomplete combustion occurs when the fuel-air mixture is excessively rich or lean, thus increasing CO emissions (Park and Lee 2014). Generally, it has been observed that DME generates lesser CO than diesel engines because of the absence of C–C bonds, high fuel oxygen and low C/H ratio. These characteristics allow far more efficient mixing and oxidation of intermediate species. Using larger injector holes and lower fuel injection pressure (FIP) than diesel results in higher CO emissions from DME-fueled engines since DME combustion requires a long injection duration. At a low local equivalence ratio, high atomization behaviour and a short ignition delay of DME results in too-lean mixture regions, which increases CO emissions. The β-scission of methoxy-methyl radicals during the combustion of DME produces formaldehyde (CH_2O), which also causes high CO emissions from DME engine than an equivalent diesel engine. CO emissions were reduced with advanced main injection and retarded pilot injection timings, according to Kim et al. (2007b), but they remained higher than with conventional single injection conditions.

Oguma et al. (2005) reported lower THC emissions from DME combustion than diesel. Ethylene (C_2H_4), ethane (C_2H_6), Propylene (C_3H_6), 1–3 butadiene (C_4H_6), benzene (C_6H_6) and toluene (C_7H_8) emissions were measured as a part of the measurement of THCs. DME operations exhibited lower ethylene, ethane, and toluene levels than diesel operations. Since these hydrocarbons can act as nuclei for PM, soot gets reduced with DME operations compared to diesel operations. However, Propylene, 1,3-butadiene, and benzene emissions were higher in DME combustion than in diesel.

Soot Emissions: Soot generation is inhibited by the absence of C–C bonds in the molecular structure of DME (Mukherjee et al. 2022). When such fuels are burned, the precursors for soot formation, such as aromatic and acetylenic species, are not produced. These aromatic species cause soot to evolve and expand with the help of acetylenic species (Karpuk et al. 1991). Ethylene (C_2H_4) and propargyl (C_3H_3) are major soot precursors. With an increase in fuel oxygen, the formation of these soot precursors decreases (Kim et al. 2011). High concentrations of free radicals drive carbon oxidation after the addition of DME, decreasing the carbon availability for synthesising soot precursors. Soot generation thrives in fuel-rich, high-temperature

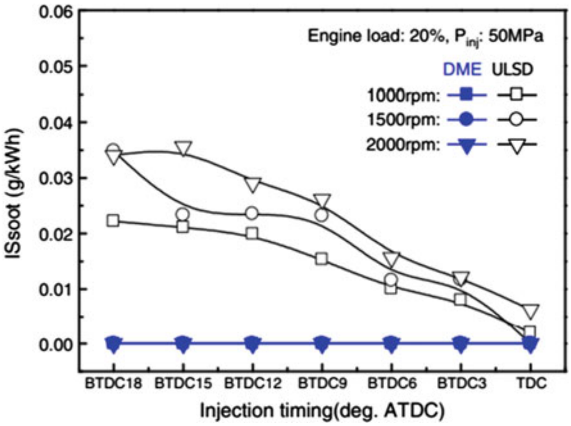


Fig. 3.19 Soot emissions from diesel and DME at varying fuel injection timings (Youn et al. 2011)

zones with temperatures ranging from 1500 to 2500 K (Park and Lee 2014; Zhao et al. 2014).

DME combustion produces virtually no soot (Fig. 3.19) (Park and Lee 2013). Due to the addition of lubricity additives and lubrication oil in fuel and oil pumps, minor amounts of soot are occasionally discovered from the DME combustion. Yoon et al. (2013) reported that soot emissions from DME-fueled engines remained minimal even when EGR was introduced due to the presence of fuel oxygen.

The reaction flow of DME is shown in the diagram under typical fuel-rich conditions (Fig. 3.20). Many researchers analysed the effects of the addition of DME and isomers of butanol on soot formation. Xu et al. (2022) reported that adding DME and butanol significantly reduced the aromatic species formation. However, DME was more effective in reducing aromatic species formation. Zhang et al. (2019) reported that the PAH formation was lower in DME than in ethanol. According to kinetic analyses, DME, with its symmetric C–O–C structure, differed from ethanol in synthesising hydrocarbon intermediates larger than C_1. As a result, DME-doped flames had lower C_2H_2 concentration than ethanol-doped flames. Therefore, DME suppressed the formation of soot precursors more efficiently than ethanol.

3.12.2 *Unregulated Emissions*

Formaldehyde (HCHO), acetaldehyde (CH_3CHO), and formic acid (HCOOH) are reported to be higher in DME than in diesel-fueled engines (Fig. 3.21) since it contains higher fuel oxygen and lubricity additives than diesel. Introducing DOC can reduce formaldehyde to insignificant levels; however, catalysts do not affect acetaldehyde emissions.

The lubricity additives blended with DME must be carefully monitored since they can impact the formation of these oxygen-based compounds. The reduction in PM could be offset by an increase in other pollutants (MacFarlane 1965; Park and

Fig. 3.20 Reaction flow diagram of soot formation during DME combustion (Xu et al. 2022)

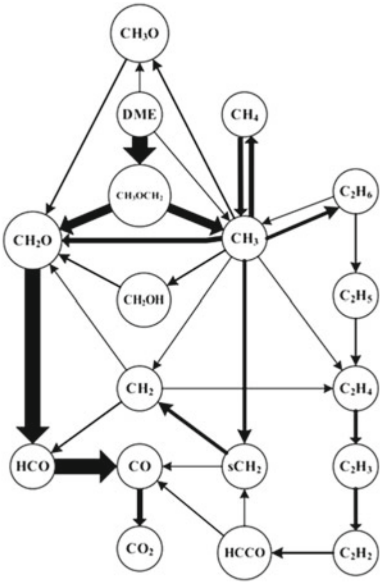
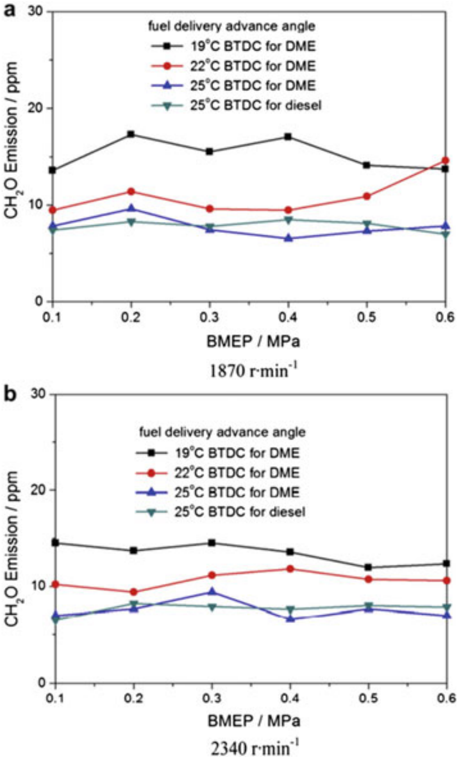


Fig. 3.21 Formaldehyde emissions from diesel and DME at varying engine speed and SoI timings of DME (Zhu et al. 2012)



Lee 2013). Formaldehyde can be produced as an intermediary in the DME engine. Also, it produces partial oxidation products in the exhaust. The average in-cylinder temperature, mixture composition and residence time influence the formation of formaldehyde as an intermediate. Outlet gas temperature and residence time affect the formation of HCHO as a partial oxidation product (Park and Lee 2013). Oxidation catalysts can be used to reduce formaldehyde to a negligible level. However, acetaldehyde emissions are high in DME combustion than in diesel, regardless of using an oxidation catalyst (Oguma et al. 2005; Jie et al. 2010). Also, methane emission is higher in DME than in diesel (Oguma et al. 2005).

3.12.3 Particulates

Policymakers are becoming conscious of regulating PM emissions as their health, and environmental impacts are severe. Especially small sized PM emissions have a significant effect on ambient air quality and human health. In locally fuel-rich zones, the combustion generates solid carbon, which is oxidised. A small fraction of fuel and lubricating oil evaporate and emerge in the exhaust as volatile or soluble organic molecules (Kittelson 1998). These soluble organic molecules contain polycyclic aromatic compounds (Quality of Urban Air Review Group 1996).

The structure of solid particulates is shown in Fig. 3.22. In locally fuel-rich zones, solid carbon is generated after combustion. A large part of the particle mass exists in the accumulation mode in the diameter range of 0.1–0.3 μm. Carbonaceous agglomerated particles and associated adsorbed materials lie in this size range (Kittelson 1998).

The size of particle determines the environmental implications of engine exhaust particles in numerous ways. It affects the particle's atmospheric residence time, optical qualities, surface area and health effects. Particles in the 0.1–10 μm diameter range have the longest residence time of approximately one week in the atmosphere. Smaller particles are removed from the atmosphere via diffusion and coagulation processes, whereas larger particles are quickly removed by settling. The average

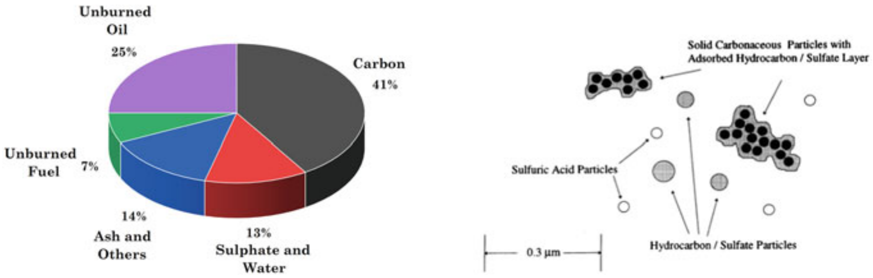


Fig. 3.22 Mineral diesel origin particulate composition (Kittelson 1998)

atmospheric residence time for nanoparticles is around 15 min (Quality of Urban Air Review Group 1996). Coagulating particles in the accumulation mode is the principal mechanism for removing these small particles (Fig. 3.23).

Diesel exhaust particles have an average surface area of around 100 m^2/g (https://www.missoulacounty.us/home/showpublisheddocument/3945/635809567464330000). The individual nuclei that make up the agglomerates have nearly all their surface area for adsorption. Thus, the size of the individual nuclei in the agglomerates, rather than the agglomeration size, determines the surface area of diesel particles.

PM emissions are significantly low for DME combustion than diesel due to 35% (w/w) fuel oxygen and absence of C–C bonds (MacFarlane 1965). Therefore, DME-powered vehicles can meet all current global soot emission regulations without using any DPF or trap. According to studies, 99% of PM emitted by a DME engine are in the nanoparticle size range, which are more harmful to human health than larger particles. However, researchers do not indicate whether tailpipe emissions risk human health regarding absolute volume and count of PM particles (Li et al. 2008).

Figure 3.24 shows that DME's particle number concentration is lower than mineral diesel under all engine operating conditions. PM from a diesel engine mainly originates from fuel combustion and lubricating oil burning in a DME engine. The consumption of lubricating oil is substantially lower than the consumption of diesel. As a result, the PM number concentration from DME combustion is significantly lower than diesel for all particle diameters. As engine speed increases, the in-cylinder flow in the chamber increases, promoting air-fuel mixing. Therefore, a more homogeneous oxygen distribution suppresses the dry soot (DS) formation. As a result, particle number concentration decreases with increasing engine speed for both diesel and DME (Wei et al. 2014).

PN concentration in the accumulation mode increases for diesel combustion with increasing the engine load at constant engine speed. At high loads, an increase in

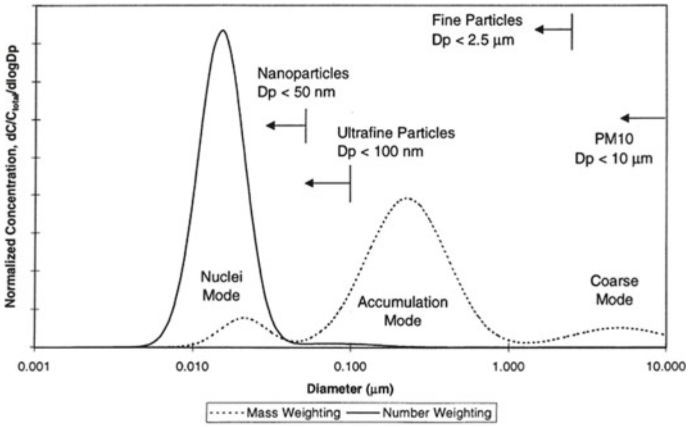


Fig. 3.23 Particle number-size distribution for diesel engines (Kittelson 1998)

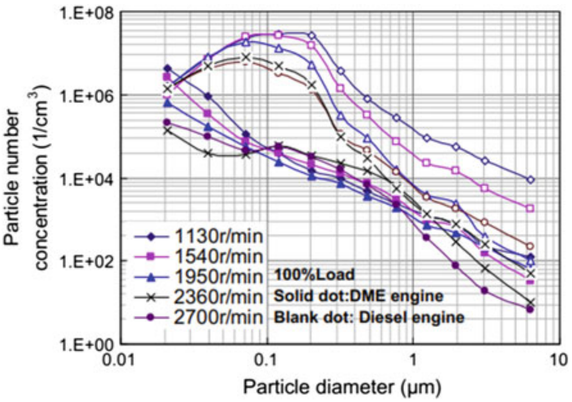


Fig. 3.24 Particle number-size distribution of diesel and DME at varying engine speeds (Wei et al. 2014)

fuel quantity increases the fuel-rich zones and the in-cylinder temperature. Therefore, soot emission from diesel combustion increases with increased engine load. The PN concentration of DME is lower than diesel because of the absence of the C–C bond and higher fuel oxygen in DME, which suppress the formation of soot (Li et al. 2008). The geometric mean diameter of the particles in the accumulation mode ($DGNs_{acc}$) increases with increasing engine load. At high loads, the concentration of soot particles increases. Therefore, many soot particles accumulate and form a chain-like structure. $DGNs_{acc}$ of diesel was 10–30 nm larger than $DGNs_{acc}$ of DME at similar engine operating conditions. Therefore, unlike diesel, small chain-like structures of exhaust particles form in DME engines. This results in lower $DGNs_{acc}$ of exhaust particles of DME than diesel (Li et al. 2008).

3.12.4 *Trace Metals*

The trace metals in the CI engine exhaust pose a serious risk to the environment and human health. Engine friction and wear debris from the combustion chamber, fuel, fuel additives and lubricating oil are primary sources of trace metals in particulates. Agarwal et al. (2010) conducted experiments using straight vegetable oils. They reported that the Iron (Fe), calcium (Ca), magnesium (Mg), and sodium (Na) trace concentrations were higher than nickel (Ni), copper (Cu), zinc (Zn), and lead (Pb), trace concentrations. Table 3.5 discusses the sources of various metallic elements present in soot.

High metal concentrations in the environment can cause serious health problems for humans and animals. Trace metal ingestion can lead to cancer, respiratory, pulmonary and neurotoxicity diseases (Geiger and Cooper 2010). Different trace metals cause various health issues in the human body, which are listed in Table 3.6.

Table 3.5 Source of various trace metals present in soot (Agarwal et al. 2003)

Element	Source component
Sodium (Na)	Coolant, additives
Magnesium (Mg)	Bearings, additives, supercharger, gearbox
Aluminium (Al)	Piston, bearings, dirt, additives, turbochargers
Silicon (Si)	Lubricants, dirt
Potassium (K)	Additives, coolant
Calcium (Ca)	Additives, greases, water
Copper (Cu)	Bronze bushings, bearings
Iron (Fe)	Cylinder liner, piston, piston rings, anti-friction bearings, gears, shafts, rust, crankshaft, valves, valve guide
Zink (Zn)	Bearings, plating, brass components, neoprene seals, additives

Table 3.6 Health effects of various trace metals (Geiger and Cooper 2010)

Element	Health effects
Sodium (Na)	Irritation to skin, eye, nose, and throat
Magnesium (Mg)	Irritate throat, nose, upper respiratory tract or mucous membrane, difficulty in breathing
Calcium (Ca)	Calcium carbonate ($CaCO_3$) dust irritates eyes, nose, mucous membranes, and skin. Contact of ($CaCO_3$) with the eyes causes eyelids redness, pain and inflammation
Copper (Cu)	Eye irritation, irritation of nasal mucous membranes, upper respiratory tract irritation, metal fume fever and nausea. Acute Cu poising can cause methemoglobinemia, liver injury, and haemolytic anaemia
Iron (Fe)	Metal fume fever, coughing, weakness, shortness of breath, fatigue, sweating and pain in muscles, fever, chills, and pain in joints
Zink (Zn)	Large doses inhalation of Zn can cause nausea, stomach cramps, and vomiting. Acute exposure to Zn oxide can result in upper respiratory tract irritation, coughing, chills and fever, substernal pain, rales
Cadmium (Cd)	Short-term effects are lung effects such as bronchial and pulmonary irritation. Long-term effects are Cd accumulation in the kidneys and affect the liver, bone, lung, nervous system and immune system
Chromium (Cr)	Short-term effect of Cr inhalation includes shortness of breath, coughing, wheezing, abdominal pain, vomiting and effects on the respiratory tract. Long-term effects of Cr inhalation are decreased pulmonary function, affected perforations and ulcerations of the septum, bronchitis, Asthma, pneumonia, soreness and nasal itching

3.13 Conclusions

Due to its favourable properties, DME is progressively used in many industries, such as transport and aerosol. DME also poses some challenges to the existing

FIE. However, DME significantly reduces emissions without compromising engine performance.

1. DME has many favourable properties such as high CN, fuel-bound oxygen, absence of C–C bond, superior spray atomisation characteristics, lower self-ignition temperature and ignition delay than mineral diesel.
2. DME also has some disadvantages, such as ultra-low viscosity, minimal self-lubrication properties, high vapour pressure, low critical point, and so on, all of which make it difficult for conventional FIE to manage DME. The lower acoustic velocity caused by DME's high compressibility also causes a long injection delay than diesel. DME is stored at a pressure higher than its vapour pressure to ensure its supply in a liquid phase. All components of the FIE are made of DME-compatible materials to avoid corrosion of parts. Lubricity additives are added to DME to improve its lubricity. Many studies showed a higher BTE of diesel than DME.
3. EGT was lower for DME due to its high latent heat of vaporisation and low in-cylinder temperature. Lower peak pressure of the DME engine was observed than mineral diesel for the same injection volume because DME has a low calorific value (28.43 MJ/kg) than diesel (42.5 MJ/kg). DME has a low HRR than mineral diesel in a premixed combustion phase. A smaller amount of DME is accumulated in the combustion chamber before the SoC due to the small ignition delay of DME. DME's peak fuel line pressure was significantly lower than diesel. DME has low fuel injection velocity and long fuel injection duration than baseline diesel.
4. Some studies indicated that DME generates lower NO_x than diesel-fueled engines due to its high CN, lower heating value, and higher latent heat capacity. Some other studies reported high NO_x emissions from DME combustion because of fast ignition and high peak in-cylinder temperature, increasing the NO_x emissions more than diesel. DME has superior spray atomisation, evaporation characteristics, and a short ignition delay, avoids the over-rich regions due to short mixing time. DME's oxygen concentration also aids in avoiding fuel-rich zones and reducing HC emissions. The use of high EGR rate increases HC emissions. Using larger injector nozzle holes and lower fuel injection pressure (FIP) than diesel resulted in higher CO emissions from DME-fuelled engines since DME combustion required a long fuel injection duration. The split injection strategy reduced the CO emission with advanced main and retarded pilot injections.
5. Soot production is inhibited by the absence of a C–C bond in the molecular structure of DME. Therefore, soot emissions were almost zero in DME combustion. PM emissions are significantly low in DME combustion than diesel due to 35% (w/w) fuel oxygen and the absence of C–C bonds. PM emitted by a DME engine were in the nanoparticle size range. Formaldehyde (HCHO), acetaldehyde (CH_3CHO), and formic acid (HCOOH) were reportedly high in DME than in diesel-fuelled engines.

3.14 Future Scope

Several studies have been conducted on DME utilisation in various engine types. Unexplored areas need to be studied for DME utilisation and improving the engine characteristics to replace diesel. These are as follows:

1. DME SoI timing should be optimised for every engine operating condition to compensate for the retarded SoI timing due to the high compressibility of DME.
2. A high-pressure fuel pump with a large plunger diameter should be explored to supply a higher DME quantity to the engine to match its entire speed-load envelope.
3. An appropriate fuel conditioning system should be developed to eliminate the chances of vapour lock in the fuel lines.
4. Durability studies should be conducted for the FIE components to analyse the DME compatibility of different materials. These results can be used for making a DME-compatible FIE for commercial applications.

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