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Prospects and Challenges of Dimethyl Ether as a Low Carbon Alternative Fuel in Internal Combustion Engines

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ABSTRACT

With fast-depleting fossil fuels and increasing environmental concerns such as climate change, the greenhouse effect, and global warming due to greenhouse gas emissions, research, and development in the field of renewable fuels is the need of the hour. Dimethyl ether is a potentially transformative alternative fuel. Its properties, such as a high cetane number (>55), absence of carbon-to-carbon bonds, low carbon-to-hydrogen ratio, high oxygen content (34.8%) in its molecular structure, and better auto-ignition property than conventional diesel fuel, make it a suitable fuel for compression-ignition engines. It is renewable as it may be produced using biomass and municipal solid waste, among other raw materials. Certain limitations of Dimethyl ether necessitate dedicated supply and storage infrastructure and a Dimethyl ether-compatible fuel injection system to make Dimethyl ether more viable as a futuristic transportation fuel. This review includes the feasibility and challenges of Dimethyl ether as an alternative fuel in internal combustion engines. The physicochemical properties, spray characteristics, advantages, limitations, and use of dimethyl ether in internal combustion engines are also discussed in detail.

Nomenclature

BMEP	Brake Mean Effective Pressure
BSEC	Brake Specific Energy Consumption
BSFC	Brake Specific Fuel Consumption
bTDC	Before Top Dead Centre
BTE	Brake Thermal Efficiency
CI	Compression Ignition
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CVSC	Constant Volume Spray Chamber
DEE	Diethyl Ether
DME	Dimethyl Ether
EGR	Exhaust Gas Recirculation
EGT	Exhaust Gas Temperature
FIS	Fuel Injection System
FIE	Fuel Injection Equipment
GHG	Green House Gas
GTL	Gas-To-Liquid
HC	Hydrocarbons
HPP	High-Pressure Pump
HRR	Heat Release Rate
ICE	Internal Combustion Engine
IS	Indicated Specific
LHV	Lower Heating Value
LPG	Liquified Petroleum Gas
MSW	Municipal Solid Waste
NO_x	Nitrogen Oxides
OEM	Original Equipment Manufacturer
PDI	Phase Doppler Interferometer
PM	Particulate Matter
PTFE	Polytetrafluoroethylene
RDF	Refuse-Derived Fuel
RNG	Renewable Natural Gas
SMD	Sauter Mean Diameter
SI	Spark Ignition
SO_x	Sulphur oxides
SPL	Spray Penetration Length
ULSD	Ultra Low Sulphur Diesel
VOCs	Volatile Organic Compounds

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1. Global Energy Scenario

All around the world, humans have relied on fossil fuels to generate the energy required for various simple and complex day-to-day processes. With the world's ever-increasing population, global energy demand is fast increasing. The combustion of fossil fuels releases greenhouse gases (GHG) responsible for global warming, the greenhouse effect, and climate change. Moreover, fossil fuels have been predicted to run out by the end of this century. It has been predicted that coal may last 216 years, natural gas may last 61 years, and oil may only last about 39 years [Wang et al. 2018]. As a result, fossil fuel prices are experiencing a steep rise. With the fast depletion of fossil fuels and the high predicted future energy demand, there is an urgency to discover a new way to meet our energy demands. This century might shift from fossil fuels to alternative biofuels such as methanol, ethanol, dimethyl ether (DME), diethyl ether (DEE), etc. In addition, using conventional crude oil-based fuels leads to the tailpipe emission of numerous hazardous pollutants that have disastrous effects on the environment and human health. The adverse effects of these pollutants are discussed in the subsequent subsection.

1.1 Environmental and Health Implications of Pollutants

Recent concerns about climate change and global warming draw attention to the contributing factors. The transportation industry makes a significant contribution. Gasoline vehicles are known to release volatile organic compounds (VOCs), carbon monoxide (CO), benzene, oxides of nitrogen (NO_x) etc., and, in the case of leaded gasoline, lead. Diesel vehicles release NO_x, VOCs, CO, and carcinogenic particulate matter (PM) [Mondal and Yadav 2019a]. Other harmful substances emitted by motor vehicles are oxides of sulphur (SO_x), carbon dioxide (CO_2), and hydrocarbons (HC). Some of these substances produce secondary pollutants that, in turn, harm the environment. Air pollution endangers health, lifestyle, and wellness, especially in urban communities. Therefore, stringent emission regulations are imposed to reduce harmful vehicle tailpipe emissions. The engine emissions can be controlled using exhaust gas after-treatment devices or by using advanced engine technologies. However, these technologies and equipment are expensive, bulky, and hard to maintain. Therefore, research on cost-effective and renewable alternative fuels is needed.

1.2 Need for Alternative Fuels

There is an apparent need for a non-petroleum-based fuel for vehicles. This alternative fuel must be clean and minimize its negative environmental effects. It must be replenished in an environment-friendly way. Accessibility must be kept in mind; the fuel should have low production, handling, and transportation costs. Large-scale global production should be possible, i.e., raw materials should be available sufficiently. In internal combustion engines (ICEs), high energy efficiency is required. Preferably, this alternative fuel must be compatible with the current infrastructure. As more research is conducted, alternative fuel vehicles are becoming more cost-efficient and performing better. The shift to alternative fuel vehicles has the potential to reduce air pollution and improve urban air quality. The eco-friendly alternative fuels that have emerged are natural gas, hydrogen, non-fossil methane, non-fossil natural gas, refuse-derived fuel (RDF), vegetable oil, biomethane or renewable natural gas (RNG), batteries and fuel cells, biofuels such as biodiesel and DME, bio-alcohol (methanol, ethanol, butanol, etc.), Fischer–Tropsch fuels, gas-to-liquid (GTL), propane, etc. Among these, researchers all over the world are currently carrying out investigations on DME as an alternative fuel to replace conventional diesel.

2. Dimethyl Ether (DME)

DME is the simplest ether compound (CH_3OCH_3). Its IUPAC name is methoxymethane. It has a high cetane number and is a next-generation alternative biofuel that can be a promising replacement for conventional diesel fuel.

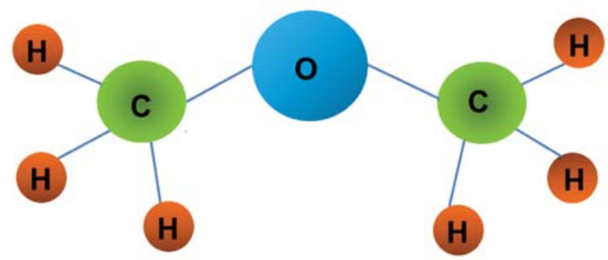


Fig. 1. Chemical structure of DME (CH_3OCH_3)

2.1 Physicochemical Properties of DME

The physical and chemical properties play an essential role in determining the suitability of fuel in an engine. The ignition characteristics of the fuel, such that self-ignition is at the proper crank angle in the cycle of operation, must be carefully investigated. The cetane number of a fuel measures the combustion ignition quality. DME has a high cetane number of over 55, while the value for diesel is around 46-55 [3,4]. DME has a low boiling point, relatively low self-ignition temperature, and is quickly vapourised. It burns with a visible blue flame. It has a sweet ether-like smell[5].It has C-O bonds, which have lower bond-breaking energies. DME's carbon-to-hydrogen ratio (C: H) is lower than diesel's. The 34.8% oxygen content in DME's molecular structure (CH_3OCH_3) is desirable since the oxygenated molecular structure and the absence of the C-C bond lead to a significant reduction of soot, CO, and unburnt hydrocarbon emissions. However, the presence of oxygen in DME leads to a significant reduction in its calorific value (~29 MJ/kg) compared to diesel (~43 MJ/kg). This limitation of DME necessitates the injection of DME fuel mass that is ~1.5 times that of diesel to produce a similar power output. Also, the injection of higher fuel mass of DME causes delayed injection. Therefore, the fuel injection system needsto be modified for DME injection. For this, the nozzle hole diameter can be increased, and the fuel injection pump of higher capacity can be used. There are no C-C bonds in DME's chemical structure, thereby leading to almost no soot formation in the exhaust emission[6].Table 1 compares various physical and chemical properties of DME and diesel.

Table 1. Properties of DME vis-à-vis Diesel fuel [Arcoumanis et al. 2008]

Fuels	DME	Diesel
Liquid density [g/m^3]	0.67	0.8"0.84
Stoichiometric A/F ratio	9.0	14.7
Cetane number	55-60	40-55
Oxygen % mass	34.8	0
C/H ratio	0.337	0.516
LHV [MJ/kg]	28.4	42.5
Vapour pressure [MPa@293 K]	0.53	<<0.001
Auto-ignition temperature K	508	523
Critical temperature [K]	400	717
Boiling point [K]	248	410-650
Surface Tension [N/m at 298K]	0.012	0.027

2.1 Production and Use of DME

DME is a multi-source fuel. It can be produced using natural gas, low-grade coal, coal bed methane, biomass, methanol, and municipal solid waste (MSW) [Arcoumanis et al. 2008]. The conventional method of production is a two-step process of indirect synthesis. The first step is the production of alcohol (methanol) using syngas. Syngas is a mixture of CO and H_2.

$$CO + 2H_2 \rightarrow CH_3OH \qquad (\Delta H° = -90.6 \text{ kJ/mol})$$

In the next step, DME is produced by the dehydration of methanol.

$$2CH_3OH \rightarrow CH_3OCH_3 + H_2O \qquad (\Delta H° = -23.4 \text{ kJ/mol})$$

Another method of producing DME is a one-step process of direct synthesis using syngas in a single reactor[8].

$$3CO + 3H_2 \rightarrow CH_3OCH_3 + CO_2 \qquad (\Delta H° = -245.8 \text{ kJ/mol})$$

DME has several uses in the contemporary world. It is currently used as an aerosol propellant, chemical feedstock, in power generation, as a liquified petroleum gas (LPG) substitute, and as an alternative biofuel in IC engines. Many countries such as Japan, Korea, the USA, Sweden, China, and Denmark have successfully developed light/medium/heavy duty trucks and mini-buses based on DME fuel and tested them under actual driving conditions.

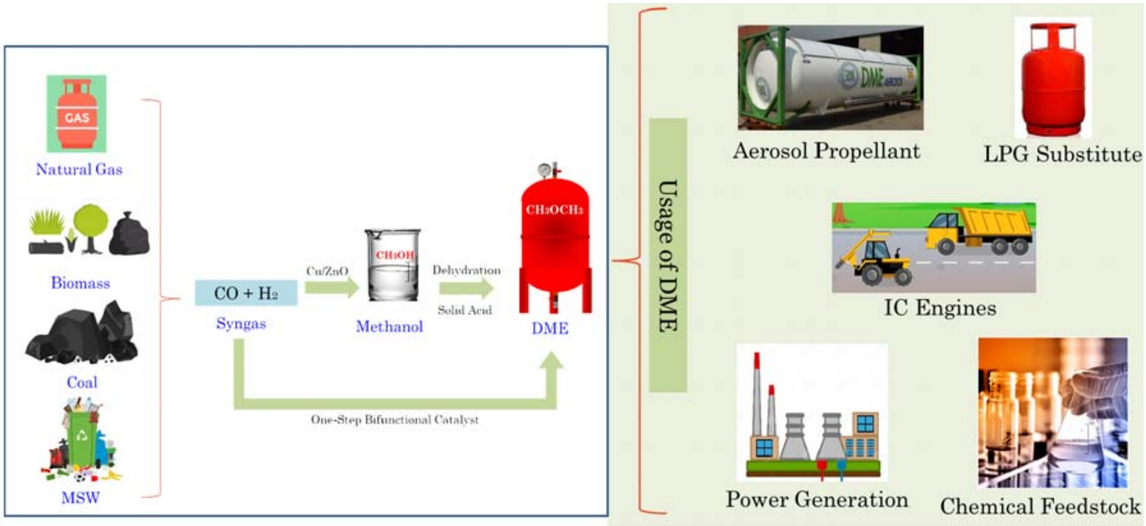


Fig.2. Indigenous Production of DME and its Usage

(a) **(b)**

Fig. 3. (a) DME-Fueled Shuttle Bus, Pennsylvania (2002) and
(b) DME-fueled bus and DME filling station in Shanghai, China (2009) [Fleisch et al. 2012]

2.3 Safety Aspects of DME

DME has been used as an aerosol propellant for years and is safely handled in bulk. It is usually known to have no negative effects on human health. Since its properties are similar to LPG, the handling is also done similarly. It is stored in liquid form in a highly pressurized storage system. Leakage problems could occur, requiring an adequate flow rate [Putrasari and Lim 2021, Mondal and Yadav 2019b]. DME is a chemically stable and almost inert compound. It is less reactive and explosive than methanol and hydrogen and does not form explosive peroxide [Semelsberger et al. 2006, Azizi et al. 2014]. It is a non-greenhouse gas and degrades easily in the troposphere. Its lower explosion limit is 3.4% by volume in air, compared to diesel's, which is 0.6% [Geng et al. 2017]. Flame luminosity is important for safety, and DME burns with a visible blue flame [Ying et al. 2006]. It has low acute and sub-chronic inhalation toxicity, and vaporised DME has no harmful effects on contact with the skin [Geng et al. 2017]. However, contact with pressurised DME can lead to severe frostbite.

3. DME as an Alternate Engine Fuel

DME as a fuel has much potential for being used in ICEs. The air-fuel mixing phenomenon governs the combustion phenomenon, and the spray characteristics determine how good the air-fuel mixing can be. Therefore, for any new fuel, the first study should be of its spray characteristics. DME's microscopic and macroscopic spray characteristics are discussed in the following session.

3.1 Spray Characteristics of DME

DME and diesel have different physicochemical properties, such as lower viscosity and lower surface tension of DME than diesel, which largely affect their spray characteristics. The spray characteristics, in turn, determine the air-fuel mixing in the combustion chamber, which governs the combustion process and, eventually, the performance and emission characteristics of the engine.

(a) Macroscopic Spray Characteristics

The macroscopic spray characteristics of a fuel include the spray penetration length, spray cone angle, radial width, and the spray area. Spray penetration length is the maximum distance between the nozzle tip and the spray's farthest point. The spray cone angle measures the extent of the spray's dispersion. The spray area is the area covered by the fuel droplets within the spray regime. All these spray parameters are calculated by post-processing the spray images that are captured using a high-speed camera. The post-processing of the images is done by using MATLAB or Image J software. Fig. 4 shows an experimental setup developed by Park et al. [2010a] for measuring DME spray's macroscopic characteristics, such as spray penetration length (SPL), spray cone angle, spray area, etc.DME was initially pressurised using compressed nitrogen gas to prevent vapour locking in the fuel injection system(FIS). DMEwas then passed through the fuel filter to the high-pressure pump (HPP) and fed to the common rail. A solenoid injector injected the high-pressurized fuel into the constant volume spray chamber (CVSC). The CVSC was maintained at high pressure using compressed Nitrogen gas. The high-speed camera was used to capture the spray images. The spray images were processed using a MATLAB code, and the spray parameters were finally calculated.

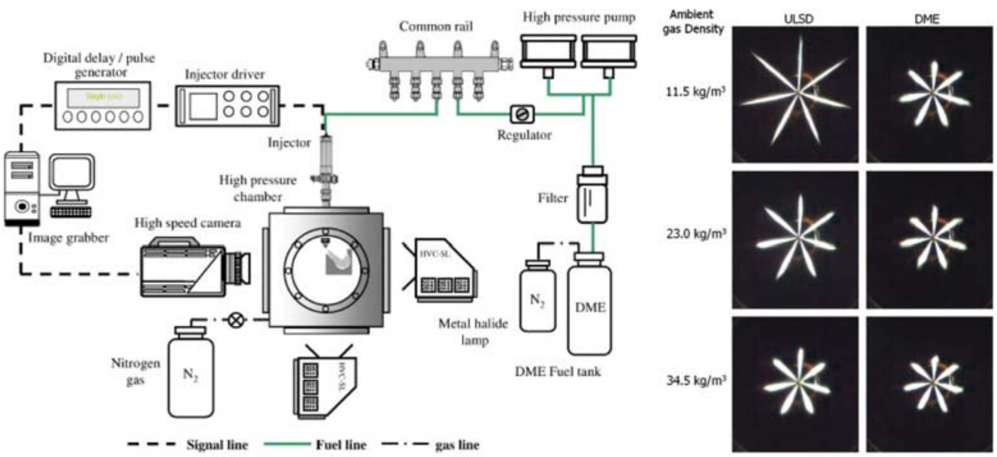
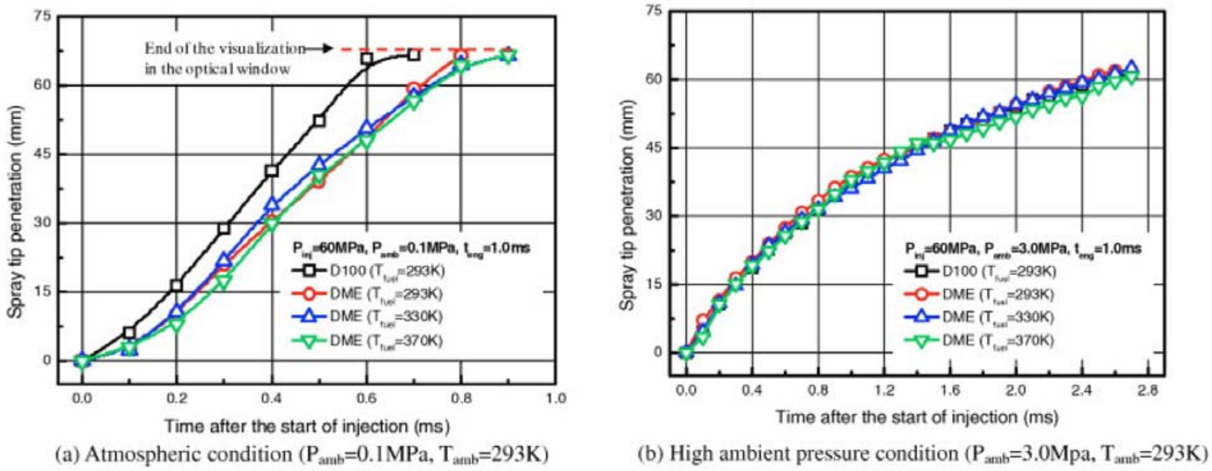


Fig. 4 (a) Experimental setup for diesel and DME spray characterisation [Park et al. 2010a], and **(b)** Spray Images of ULSD and DME at different ambient gas densities [Youn et al. 2011]

An optimum spray penetration length prevents the wall-wetting effect and thus prevents the burning of the lubricating oil, lowering the unburnt hydrocarbon emissions. Researchers have reported a lesser spray penetration length of DME than diesel [Youn et al. 2011, Park et al. 2010b]. The spray images of ultra-low sulphur diesel (ULSD) and DME are shown in Fig.4(b). It can be seen that DME's spray penetration length was lower than ULSD's. The penetration length decreased for both fuels on increasing the ambient gas density. Fig.5(a) shows the effect of fuel temperature on the spray penetration length of diesel and DME at atmospheric pressure of 1 bar. D100 represents 100% diesel. Diesel's SPL was higher than DME for all the cases. The fuel temperature didn't have any major effect on DME's SPL. It can be seen from Fig.5 (b) that at a high ambient pressure of 30 bar, the SPL was almost the same for diesel and DME at all fuel temperatures.

Fig. 6(a) shows the spray cone angle of diesel and DME at an atmospheric pressure of 1 bar. It can be seen that DME's spray cone angle was greater than that of diesel. A greater spray cone angle helps in good air-fuel mixing, which improves combustion. On increasing the fuel temperature, DME's spray cone angle increased slightly. Fig. 6 (b) shows that at a higher ambient pressure of 30 bar, the spray cone angle of diesel and DME became almost similar.



(a) **(b)**

Fig. 5 Spray tip penetration of diesel and DME at various fuel temperatures for (a) atmospheric conditions of 1 bar and (b) ambient conditions of 30 bar [Park et al. 2010b]

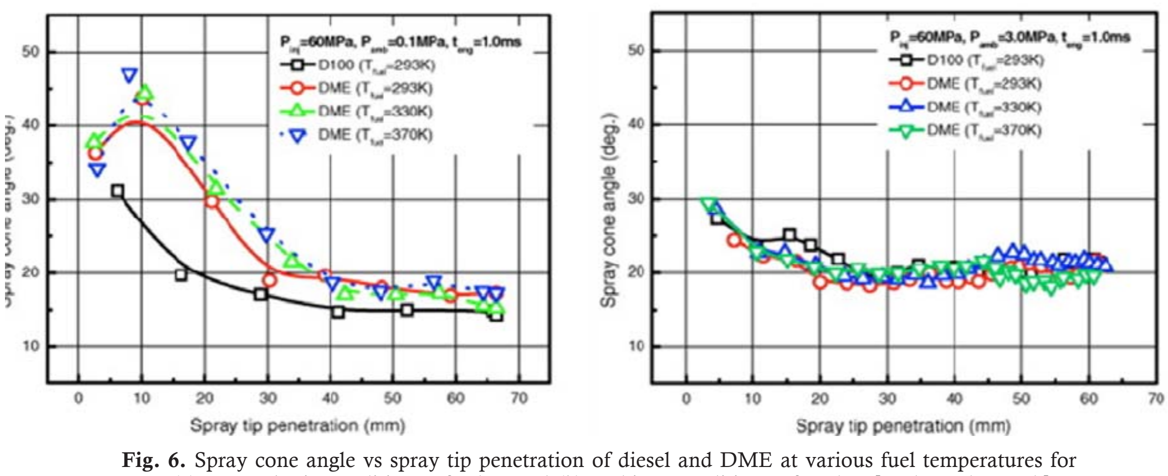


Fig. 6. Spray cone angle vs spray tip penetration of diesel and DME at various fuel temperatures for **(a)** atmospheric conditions of 1 bar and **(b)** ambient conditions of 30 bar [Park et al. 2010b].

(b) Microscopic Spray Characteristics

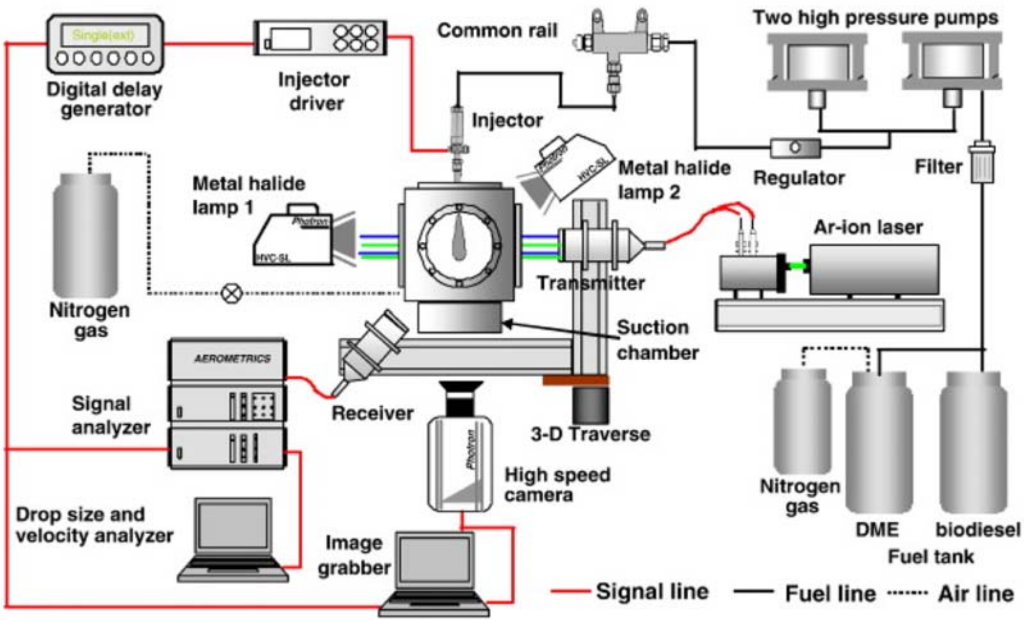


Fig.7 Experimental setup for microscopic spray characterization of DME

Microscopic spray characteristics of a fuel spray are measured using a high-intensity illumination source and phase Doppler interferometer (PDI). The microscopic spray parameters include droplet size, droplet velocity, and droplet distribution. Fig. 7 shows the experimental setup for microscopic spray characterization. The Sauter mean diameter (SMD) is defined as the diameter of a droplet with the same volume to the surface are a ratio as the entire spray. Fig. 8(a) shows the SMD values of DME and diesel. It can be seen that the DME droplets have smaller SMD compared to diesel. This was due to the lower kinematic viscosity and lower surface tension of DME, leading to the formation of finer DME droplets. The smaller size of DME droplets exhibits its superior atomization properties. Fig. 8 (b) shows the mean axial velocity of diesel and DME droplets. It can be seen that the axial velocity of both fuels is almost the same everywhere except near the nozzle tip [Suh et al. 2006].

3.2 DME Storage and Handling

DME has a saturation pressure of 5 bar at atmospheric conditions of 0.1 MPa and 298 K [Mehra and Agarwal 2022]. Therefore, it needs a pressurised system to prevent vapour locking. DME's physical properties are similar to LPG; therefore, storage tanks similar to LPG can be used for DME. Lubricity enhancers like Lubrizol (1000 ppm), Hitec-560 (100 ppm), Infineum R655 (500 ppm), 2% castor oil, and biodiesel should be added in appropriate concentrations while filling the DME tank since DME's lubricity is very low [Agarwal et al. 2023]. The sealant material in the valves and tanks should be DME compatible, such as Teflon, poly tetrafluoro ethylene (PTFE), etc. [Pal et al. 2021]

3.3 Fuel Injection Equipment (FIE) for DME

DME's low boiling point (-25°C) and high vapour pressure necessitate a closed pressurised fuel injection system. DME should be pressurised well above 5 bar at atmospheric conditions to prevent vapour locking and cavitation in the FIS. A pneumatic or electronic pre-supply feed pump can be used for this purpose. Furthermore, DME has a low bulk modulus and, thus, higher compressibility than diesel; therefore, the high-pressure fuel injection pump should be of higher capacity than diesel if the same power output is achieved. The injector's nozzle hole diameter can also be increased for injecting higher DME mass [Mukherjee et al. 2022a, Mukherjee et al. 2022b]. The return fuel line that carries the DME fuel should be cooled down by using a heat exchanger so that it doesn't increase the DME tank's temperature and eventually vaporise it, causing vapour locking in the FIS. Fig.9 shows the experimental setup of a DME-fuelled four-cylinder engine with a common-rail fuel injection system.

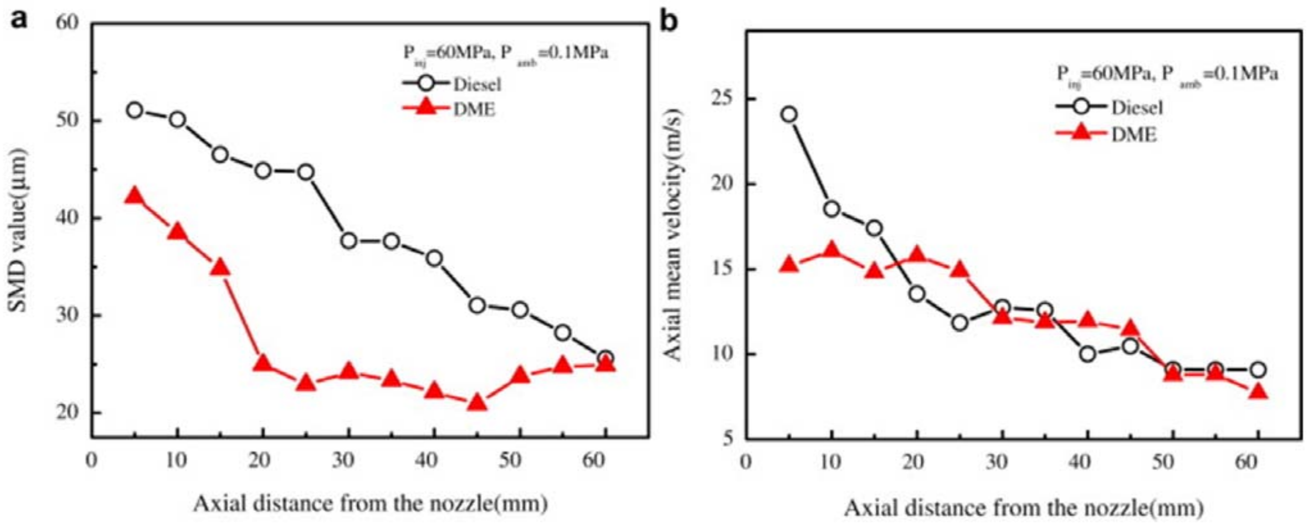


Fig. 8 (a) SMD vs axial distance from the nozzle and **(b)** Axial mean velocity vs axial distance from nozzle of diesel and DME [Suh et al. 2006]

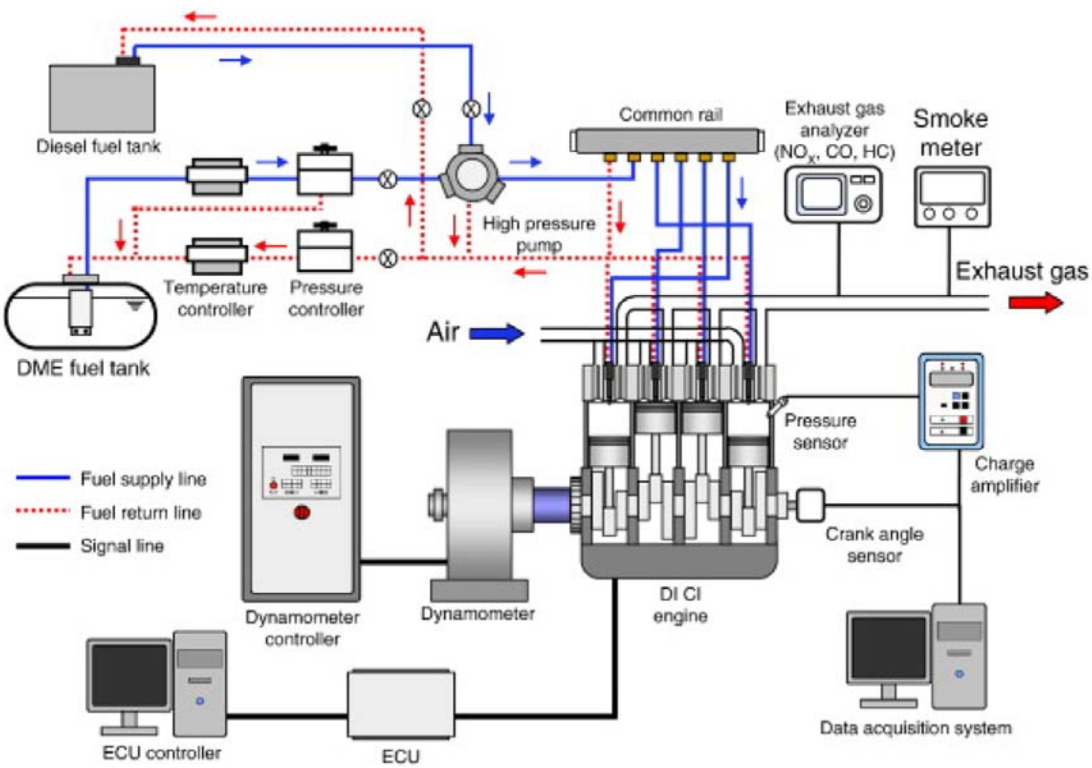


Fig.9 Schematic of a DME-fuelled four-cylinder engine [Youn et al. 2011]

Some of the common characteristics that ascertain the suitability of alternative fuels for use in spark ignition (SI) and compression ignition (CI) engines are the octane and cetane numbers, respectively, and their atomisation and vaporisation characteristics, lower heating value (LHV), cost-effectiveness, and availability of infrastructures [Sorensen S.C. 2001]. The superior properties of DME, like high cetane number (>55), low boiling point (-25 °C), and high oxygen content in its molecule (35% by weight) compared to conventional diesel, make it a promising alternative fuel for CI engines. DME vaporises immediately after the injection. It has a high compressibility, resulting in relatively low fuel injection pressure [Ying et al. 2006, Ying and Longbao 2008]. The absence of a carbon-carbon bond and lower carbon/hydrogen ratio in the DME molecule leads to almost smokeless combustion [Azizi et al. 2014]. DME engines do not have a trade-off between NO_x and PM emission, providing high exhaust gas recirculation (EGR) tolerance [Fleich et al. 2012, Salsing et al. 2012]. A study by Xu et al. [2012] showed that the basic injection system was sufficient for the working of DME-fueled engines.DME can be used in three application modes in CI engines [Stepanenko and Kneba 2019].

i. **100% DME mode**: DME has a high cetane number, shortening its ignition delay. It also has a low self-ignition temperature, leading to faster combustion. Therefore, it can replace diesel fuel completely in a CI engine. However, DME being a gas at room temperature (0.1 MPa and 298 K), direct injection of 100% DME in the fuel injection system (FIS) of conventional diesel engines would require some significant modifications due to DME's incompatibility with elastomers, lower values of lubricity, viscosity, and calorific value. This makes the single-fuel mode technically complex and expensive.

ii. **Dual fuel combustion mode:** DME can also be ignited in the dual fuel mode by inducting the gaseous form of DME into the intake manifold with a pilot injection of diesel. Gaseous DME forms a homogeneous mixture with air and is ignited by directly injected diesel in the cylinder. The system requires minor modifications, making it less expensive.

iii. **Blended mode**: DME exhibits good solubility with many hydrocarbon fuels like diesel, biodiesel, LPG, butane, and ethanol without solubility problems. The blending of DME with propane improves the LHV of DME, while the DME/biodiesel blended fuel compensates for DME's low lubricity and viscosity. The blended fuel emission level is lower than that of conventional diesel [Kim and Park 2016, Park and Lee 2014]. This mode does not require major modifications in the fuel supply system.

Table 2: Comparison of the production process and characteristics of diesel and DME [Takeshita T. 2010]

Properties/Characteristics	Diesel	DME
Energy Density	High	Low
Production Cost	Moderate	Moderate
Distribution Infrastructure	Complete	Very Low
Current Production and Retail Availability for Vehicles	Complete	Very Low
Compatibility with Existing IC Vehicles	Complete	Requires Conversion
Typical GHG Emissions	High	Moderate

3.4 Combustion and Performance Characteristics of DME Engines

DME's low viscosity and surface tension cause its distinct spray characteristics, such as lower spray penetration and greater spray cone angle than diesel. The spray characteristics influence air-fuel mixing, which is a vital factor in determining the combustion process in a CI engine [Suh et al. 2006]. It is essential to study the combustion characteristics of DME [Putrasari et al. 2016]. Yu et al. [2010] studied the effect of DME supplements on spray characteristics and atomisation quality of diesel fuel, which shows a significant impact on its spray characteristics due to the micro explosion and flashboiling effect of DME. DME has a low boiling point and high evaporation rate compared to diesel. It evaporates immediately, forms an ignitable mixture with air, and decreases ignition delay. Ignition delay of the fuel has a crucial effect on combustion characteristics and impact on exhaust emissions. The high cetane number, excellent vaporisation property, and superior atomisation performance also cause rapid DME combustion reactions in a relatively shorter duration. The greater oxygen content of DME (34.8%) acts as an oxidiser during the process of combustion, which promotes the combustion reaction and increases the in-cylinder temperature [Park and Lee 2014].

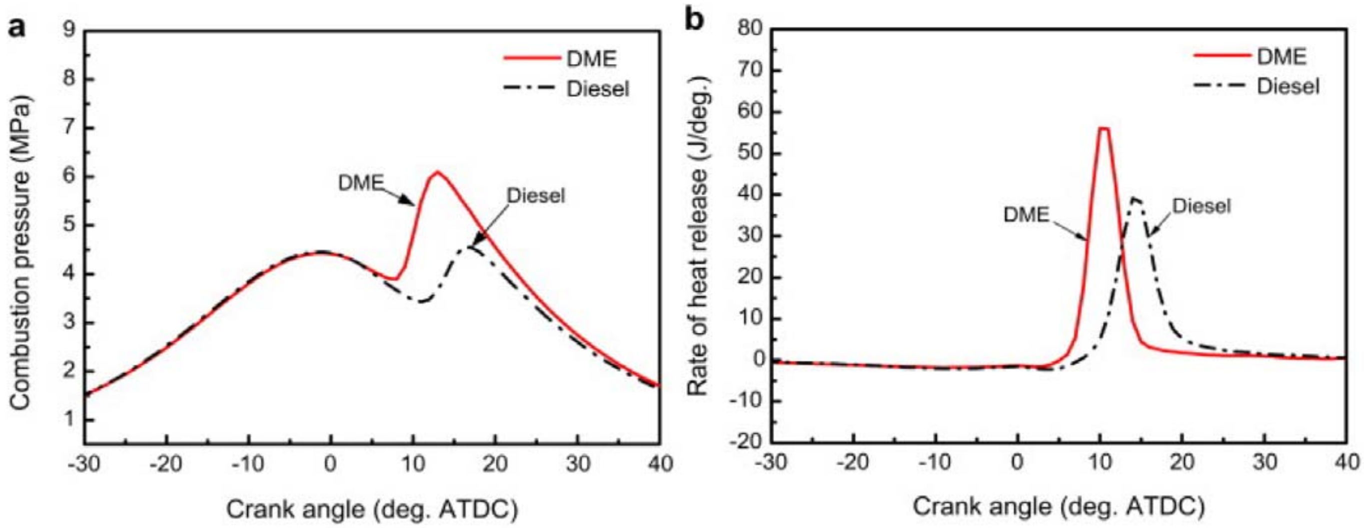


Fig. 10 (a) Combustion pressure vs. Crank angle and
(b) Rate of heat release vs. crank angle for diesel and DME [Kim et al. 2008, Zhang et al. 2008].

Due to DME's low density, low viscosity, high compressibility, and high vapour pressure, a high-pressure injection pump of higher capacity than dieselis required. A common rail-type high-pressure fuel injection system with electronic control is the best for DME engines [Mondal and Yadav 2019a]. A study was conducted to understand the internal nozzle flow of DME and its effect on spray evolution/formation inside the combustion chamber. Due to its high vapour pressure and low viscosity, it causes cavitation in the injector nozzle holes. It can lead to poor spray tip penetration inside the combustion chamber, resulting in high CO emissions [Mohan et al. 2017]. The mass of fuel injected should be increased upto nearly 1.5 times that of diesel for a similar energy input of diesel [Park and Lee 2014, Ying and Longbao 2008]. Kim et al. [Kim et al. 2008] studied the combustion characteristics of a DME-fuelled engine and reported a higher in-cylinder pressure and heat release rate of DME than diesel. They attributed the higher cetane number and shorter ignition delay of DME as the reasons behind this. DME showed earlier combustion than diesel due to its superior atomisation and vaporisation characteristics.

In another study, Kim et al. [2011] studied the effect of advanced injection timing on the DME combustion, as shown in Fig. 11. At retarded injection timings from BTDC 10° to 20°, the peak in-cylinder temperatures were highest since the combustion occurred at concentrated regions of the rich air-fuel mixture. At advanced injection timing, from BTDC 30° to BTDC 60°, the in-cylinder temperatures dropped and were similar. At these conditions, injected fuel was present in the piston bowl. A homogeneous air-fuel mixture was formed before ignition. However, incomplete combustion occurred on further advancing the injection timing to BTDC 70°, and the in-cylinder temperature dropped due to the lack of oxygen at the squish region. Also, HC, CO and soot emissions increased on advancing the injection timing beyond BTDC 60° for DME.

Fig. 10 (a) shows the variation of torque and power output with the engine speeds for diesel and DME fuels. The DME-fuelled engine performed better than diesel since DME's torque and power output were higher than diesel. Ying et al. [2006] investigated the performance of the DME-diesel blended fuelled engines. DM10 represents 10% DME and 90% diesel blend. Fig. 12 (b) shows that the power output decreased on

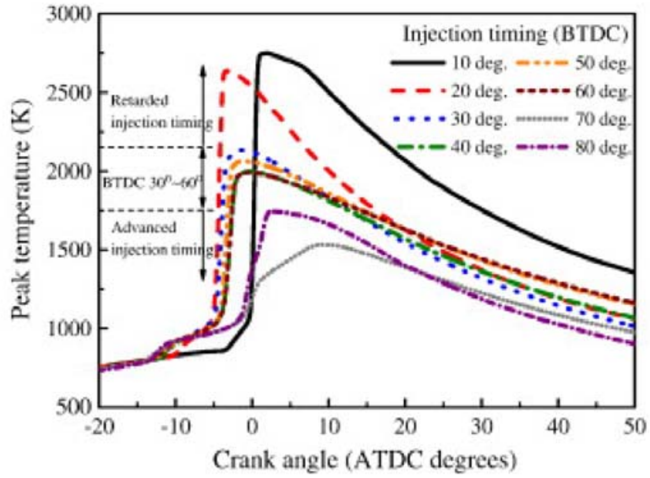
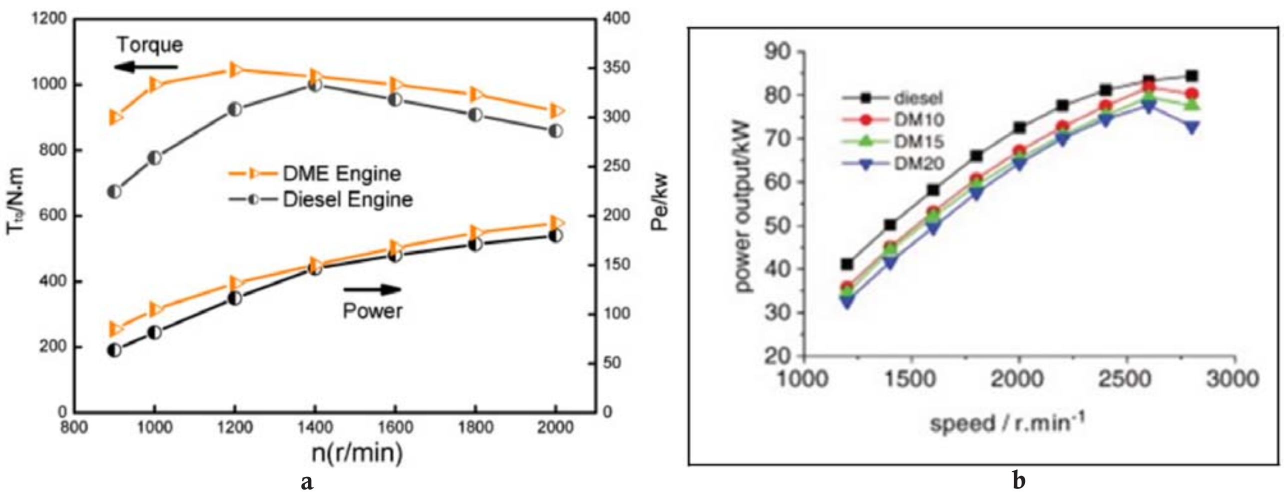


Fig. 11 Effect of injection timing on
peak in-cylinder temperatures w.r.t. crank angle [Kim et al. 2011]



a **b**

Fig. 12 (a) Torque and Power Output vs engine speed for Diesel and DME fuelled engines [Kim et al. 2008] and
(b) Comparison of power outputs among Diesel and Diesel-DME blended fuels [Ying et al. 2006]

adding DME to diesel. A higher DME blend percentage resulted in lower power output. The lower LHV of the blended fuels compared to diesel and the lesser value of injected blended fuels due to their lower density were the reasons behind the lower power output of the diesel-DME blended fuels. The power output can be increased by increasing the quantity of blended fuel per cycle [EPA A. 2011]. In another study done by Agarwal et al. [2023], as shown in Fig. 13, the DME engine showed higher brake thermal efficiency (BTE) and lower brake specific energy consumption (BSEC). The brake-specific fuel consumption (BSFC) was higher for DME to produce similar power output since DME has a lower calorific value. The torque and power output of the DME-fuelled engine were comparable to that of diesel engines. The exhaust gas temperature (EGT) of DME fuelled engine was comparatively lower than that of the diesel engine.

3.5 Regulated and Unregulated Emissions of DME Engines

NO_x, HC, CO, and PM are known as regulated emissions. Other hydrocarbons, such as formaldehyde, unburned DME, carbon dioxide (CO_2), etc., are known as unregulated emissions [TunérM. 2015]. While using 100% DME-fueled engine systems, the emission characteristics depend mainly upon engine specifications, fuel supply systems, engine operating conditions, and the injection strategy. The effect of fuel injection timing on regulated and unregulated emissions was investigated, and it was found that engine emissions vary intensively with the change in fuel injection timings [Zhu et al. 2012].

3.5.1 Regulated Emissions

(a) Oxides of Nitrogen

NOx emission is affected by combustion temperature, combustion duration, equivalence ratio, and oxygen content. The NO_x emissions of diesel and DME-fuelled engines show mixed trends. Some studies have reported that DME-fuelled engines have higher NO_x emissions than diesel engines, whereas others have found contrarian results [Stepanenko and Kneba 2019, Park and Lee 2014]. Lower NO_x emission in DME-fuelled engines was due to the high cetane number and higher enthalpy of vaporization, leading to a small amount of pre-mixed burned DME and, therefore, low combustion temperature. The lower heat release rate (HRR) in the pre-mixed combustion phase due to lower LHV than diesel contributed to lower adiabatic flame temperature and low NO_x formation [Bae and Kim 2017]. As reported in some studies, the higher NO_x emission in DME engines was due to short ignition delay under the same energy input conditions. Youn et al. [2011] reported higher NO_x emissions from DME-fuelled engines than diesel engines. They attributed DME's shorter ignition delay responsible for its faster combustion in high combustion temperatures than that of diesel. With the increased engine load, more fuel was required to be burnt, causing higher cylinder temperature and high NO_x emission [Tunér M. 2015]. With the advancement of the injection timing of DME, the fast initiation of heat release in the pre-mixed combustion phase caused the increase in the in-cylinder temperature, where the remaining fuel might burn at higher temperature conditions compared to diesel fuel. This higher built-up temperature condition caused higher HRR, leading to higher NO_x formation [Bae and Kim 2017]. EGR is the best strategy to reduce the burned gas temperature in the cylinder and reduce NO_x formation [Park and Lee 2014].

The study by Zhu et al. [2012] reported 50% lower NO_x emission from a DME-fuelled engine than diesel at similar fuel injection timing. The NO_x emission further decreased for DME on retarding the fuel injection timing from 25° to 19°b TDC. They attributed the high latent heat of vaporisation of DME, which led to lower in-cylinder temperature and consequently lower NO_x.

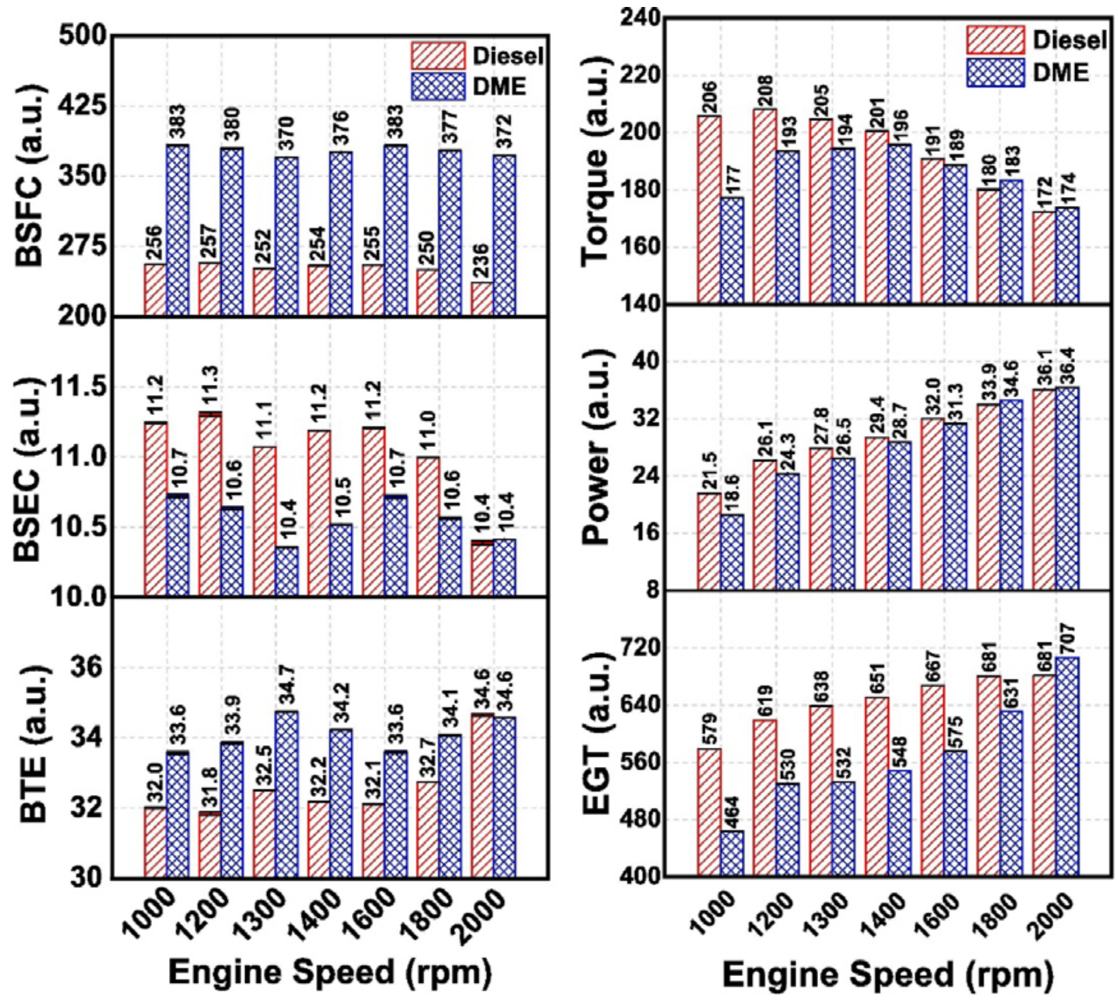


Fig. 13 (a) BTE, BSEC, and BSFC, and (b) EGT, Torque, and Power of DME- and diesel-fuelled engines at varying engine speeds and full load conditions. [Agarwal et al. 2023]

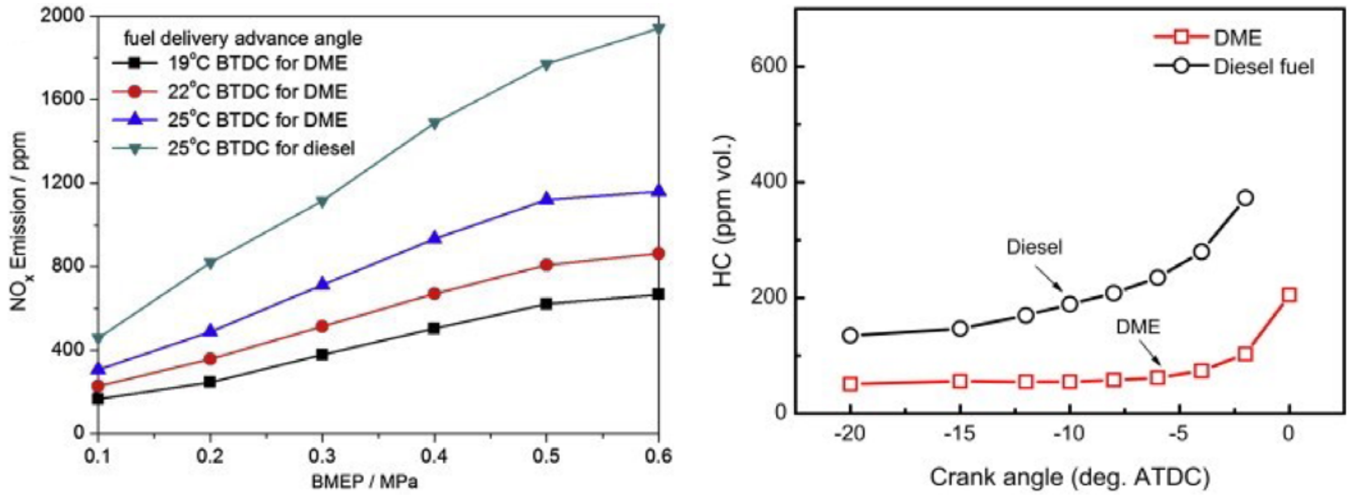


Fig. 14 (a) NO_x emission vs. BMEP for diesel and DME [Zhu et al. 2012]and **(b)** HC emission vs. crank angle for diesel and DME [Park and Lee 2013]

(b) Hydrocarbons

The HC emissions result from the unburnt fuel and burning of the lubricating oil. Fig. 14 (b) shows lower HC emission from the DME-fuelled engine than diesel due to the oxygenated molecular structure of DME and a lower C/ H ratio, which caused efficient combustion.

(c) Carbon Monoxide

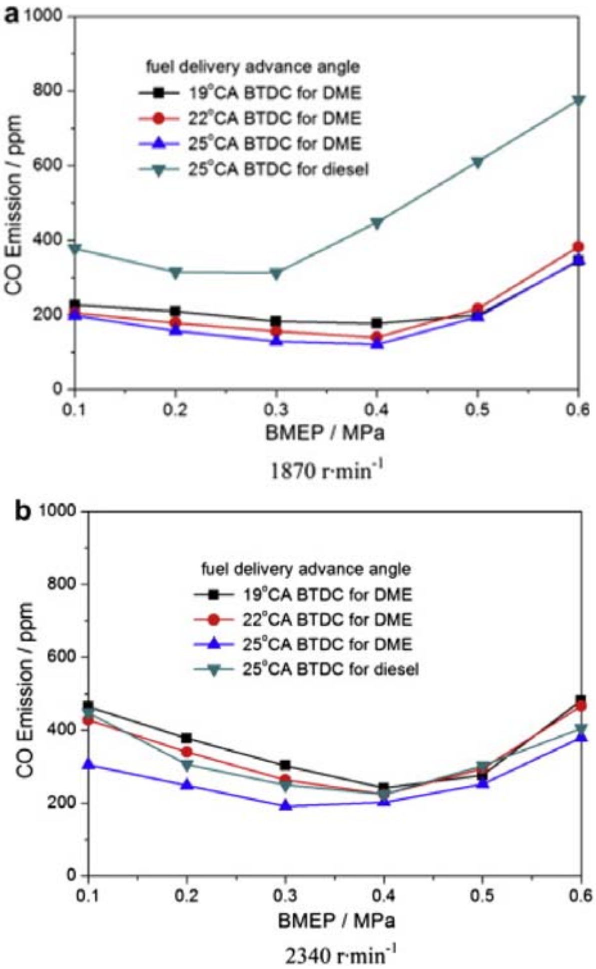


Fig. 15 CO emission vs. BMEP for diesel and DME at **(a)** low engine speed of 1870 rpm and **(b)** higher engine speed of 2340 rpm [Zhu et al. 2012]

Zhu et al. [2012] reported considerably lower CO emissions from a DME-fuelled engine (Fig. 15a) than diesel at lower engine speeds. However, when the engine speed increased, the CO emission increased for DME (Fig. 15 (b)). CO emission is caused by incomplete combustion, which primarily depends on the local fuel-air ratio. Too lean or too rich mixtures result in the formation of CO. Otherwise, it can be post-oxidised if the temperature is high enough. DME fuel possesses better spray atomisation characteristics, low C/H ratio, lack of C-C bonds, and high oxygen content, which facilitates good mixing and fast oxidation of intermediate species compared to diesel fuel. It results in smooth combustion and low CO emissions [Ying and Longbao 2008].

(d) Particulates

Particulate matter (PM) emissions from DME-fuelled engines were significantly reduced than diesel [Arcoumanis et al. 2008]. Fig. 16 (a)

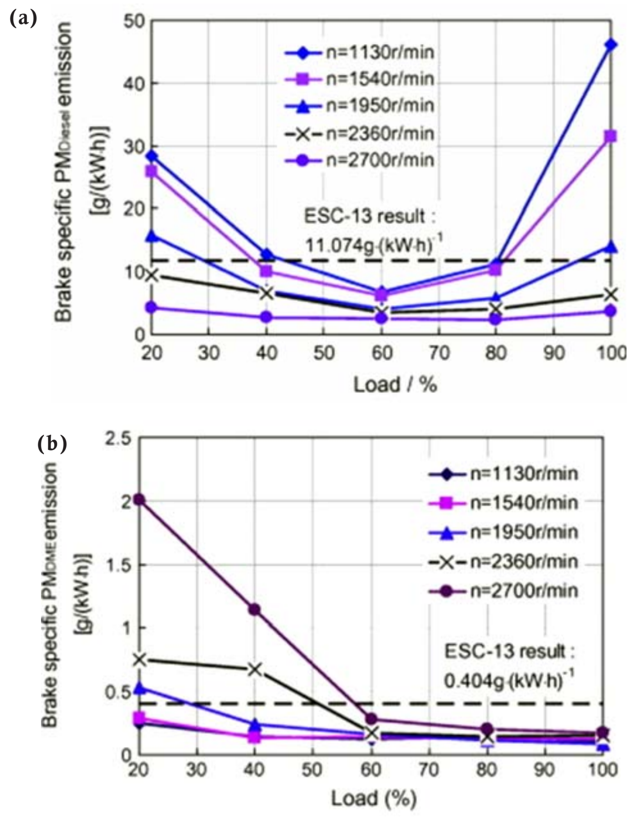


Fig. 16 Brake-specific PM emission from **(a)** diesel fuelled engine and **(b)** DME fuelled engine [Wei et al. 2014]

and (b) show the brake-specific PM mass emissions from diesel and DME engines. The highest PM mass emission from the DME-fuelled engine was at the low load and high engine speed operating condition. At full load, the PM emission from the DME-fuelled engine was almost negligible compared to the diesel-fuelled engine, for which the PM emission increased substantially [Wei et al. 2014].

3.5.2 Unregulated emissions

(a) Formaldehyde

Formal dehyde (CH_2O) is a significant unregulated emission from CI engines. It is toxic, allergenic, and carcinogenic [Tunér M. 2015]. CH_2O is a product of the incomplete combustion of HC. For diesel, CH_2O is formed from the methoxy decomposition reactions, while for DME, CH_2O is formed from the â–scission of the methoxy–methyl radicals. DME and diesel were reported to have the same level of CH_2O- of around 8 ppm at the same engine operating conditions [Zhu et al. 2012].

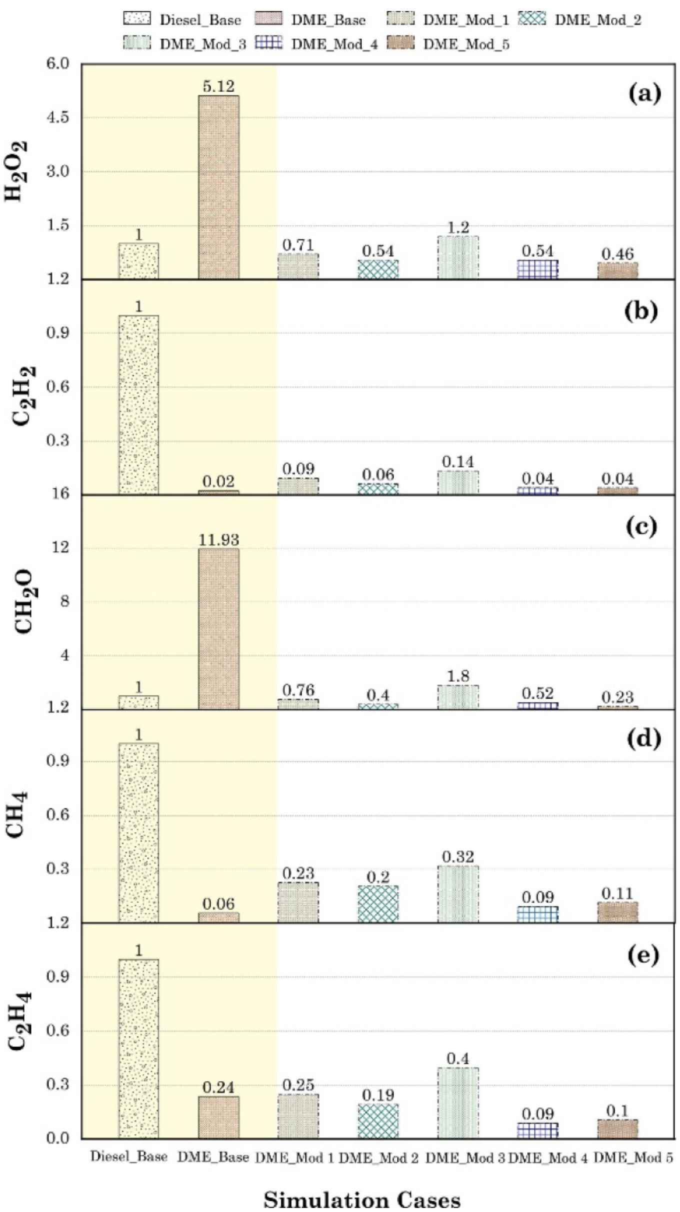


Fig. 17 Unregulated emissions for baseline diesel, base DME, and modified DME fuel injection equipment cases [Mukherjee et al. 2022b]

In a computational study done by Mukherjee et al. [2022b], as shown in Fig. 17, they reported significantly higher CH_2O emissions from the DME engine than the baseline engine when the engine was unmodified for DME. However, with the optimised fuel injection equipment cases, the CH_2O emission was reduced from the DME engine.

(b) DME

DME emission results from unburned fuel in too-rich or too-lean areas in the combustion chamber. In the study by Zhu et al. [2012], the fuel injection pressure was only 25 MPa, leading to a shorter spray penetration length of DME. This led to the presence of DME vapors in limited regions, leading to poor air-fuel mixing and, therefore, higher DME emission at low load conditions. However, at higher loads, as the amount of fuel increased, burning of which led to higher in-cylinder temperature. The higher in-cylinder temperature caused post-oxidation of unburnt DME and, consequently, lower DME emission. DME emission changed slightly with the change of engine loads under a given engine speed and injection timing [Zhu et al. 2012].

The DME emission can also be controlled by optimising the injection timing.

Fig. 18 shows the DME emission from a DME-fuelled engine at three different injection timings. The unburnt DME emission in the exhaust gases was reduced by advancing the fuel injection timing from 19 to 25° b TDC. This was because of the shorter ignition delay, which led to more time for the mixing-controlled combustion and, therefore, more proper and complete combustion of DME [Heywood J. B. 1988]. The unburnt DME gets oxidised in the post-flame regions.

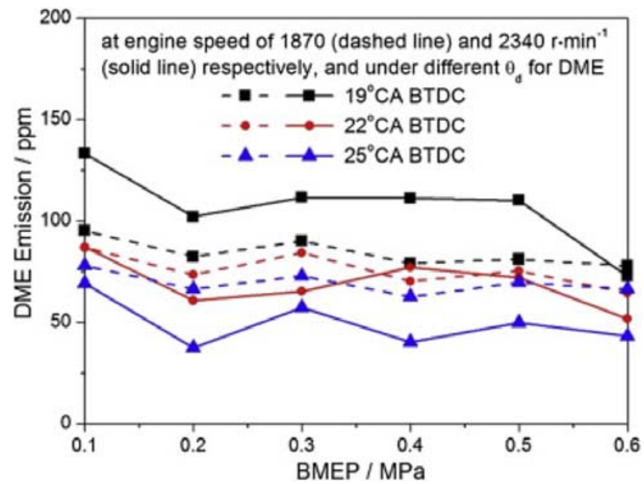


Fig.18 DME emission (ppm) vs. BMEP (MPa) from a DME-fuelled engine [Zhu et al. 2012]

(c) Soot and Smoke

The soot emission from DME-fuelled engines is almost 0 at all operating conditions. This is because of the absence of the C-C bond and the absence of soot precursors such as acetylene (C_2H_2), ethylene (C_2H_4), and propargyl (C_3H_3) [Arcoumanis et al. 2008]. Fig. 19 compares indicated specific (IS)-soot emission from diesel and DME-fuelled engines. DME has a C-O-C molecular structure and high oxygen content. Therefore, DME engines have almost no soot formation under all operating conditions [Zhu et al. 2012]. Some negligible amount of soot formation may occur in the DME engines due to the burning of the lubricating oil [Xinling and Zhen 2009].

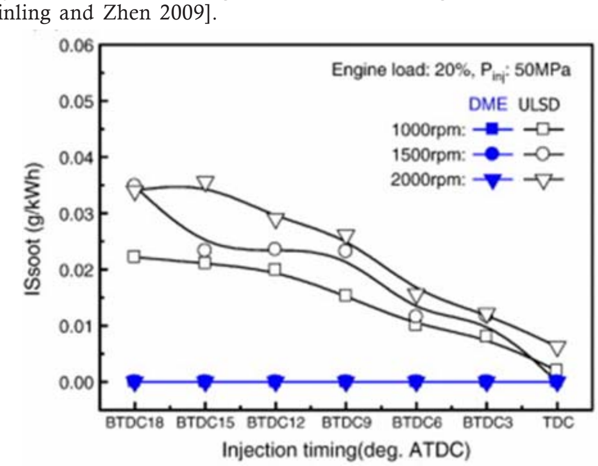


Fig. 19 ISsoot emission vs injection timing for DME and ULSD at different engine speeds [Youn et al. 2011]

(d) Other Emissions

It can be seen from Fig.17 that the emissions of C_2H_2, CH_4 and C_2H_4 were considerably lower for DME than diesel. This can be attributed to the presence of an oxygen atom and the absence of a C-C bond in DME's molecular structure. However, it can be seen from Fig. 17 that the H_2O_2 emissions from the DME engine were higher than that of diesel. This was attributed to the oxidation of methoxy (CH_3O) during the combustion of DME, which resulted in the formation of H_2O_2 [Mukherjee et al. 2022b].

4. Advantages of DME over Conventional Diesel

DME can be used in ICEs with some modifications in the fuel supply system. Due to its high cetane number, it displays shorter ignition delay and overall greater ignition ability. Due to its low boiling point, it vaporises instantly when injected into the cylinder. Due to the gradual rise in pressure in the pre-mixed burning stage, combustion noise is lower from DME-fuelled engines than from diesel. DME can be blended with other fuels like diesel, biodiesel, LPG, etc.DME has similar physical properties as LPG, so LPG's transportation and storage infrastructure can be adapted for DME. Since it has no direct C–C bonds and a low carbon-to-hydrogen ratio, there is lesser emission of CO_2, CO, and HC, and almost zero soot emission compared to other fuels, which negates the use of particulate filters in the after-treatment system [Smolec et al. 2017]. The greatest advantage of DME is that it can be indigenously produced from renewable feedstock such as biomass and municipal solid waste (MSW), decreasing the dependency on crude oil imports. This would also lead to lower fuel prices and open employment opportunities to a large section of society.

5. Challenges of DME Engines

Although the use of DME as an alternative fuel started in the 1990s, fully DME-fuelled commercialised vehicles are still at the research and development level. More research is required to improve DME engine performance [Kim and Park 2016]. Below are some challenges to implementing DME as a viable option as an alternative fuel for IC engines:

i. **Low Viscosity:** DME's viscosity is 1/10th of that of diesel. This causes a high leakage rate through small clearance of the injection pump plunger and injection nozzle [Putrasari and Lim 20218]. A low viscosity also implies poor lubricity, causing wear and tear of the high-pressure pump and leakage issues in the FIE.

ii. **Low Lubricity:** This property is essential for the satisfactory performance of diesel engines because it relies on the fuel to lubricate moving parts of the fuel injection system. Low lubricity causes premature wear and failure of pumps and fuel injectors. Lubricity additives like Lubrizol, castor oil, biodiesel, etc., are imperative to run DME-fueled engines. The concentration of lubricity additives must be carefully decided since more of it than required may lead to increased unburnt hydrocarbons in the exhaust emission from DME-fueled engines.

iii. **Low Energy Density:** Due to the presence of an oxygen atom in its molecule, the calorific value of DME is decreased. The lower calorific value calls for a greater fuel flow rate, longer injection duration, and advanced injection timing to match the power output of diesel. There is a need to develop additives that can enhance the heating value of DME fuel. DME's low fuel density and low heating value mean that a larger fuel tank is required compared to conventional diesel fuel [Kim and Park 2016]. This would add to the vehicle's weight and lessen the space in the vehicle [Zubel et al. 2021].

iv. **Vapour Locking and Cavitation:** DME has a low boiling point and exists in gaseous form at standard conditions (0.1 MPa and 298 K). The fuel's high vapour pressure results in occasional cavitation, obstructing the stable fuel injection systems. Therefore, the fuel injection system must be pressured (greater than 5.1 bars at 25°C) and liquified for storage and handling [Kim and Park 2016].

v. **Material Incompatibility:** DME is incompatible with elastomers, rubber, and plastic since it tends to dissolve them [Park and Lee 2014]. Therefore, DME-compatible materials such as Teflon and PTFE should be used as sealing material [Kim and Park 2016].

vi. **Cost:** To promote the use of DME as an alternative fuel on a large scale, the price of the fuel should be competitive or lesser than conventional fossil fuels. From a cost perspective, simple and easy comparative figures are a key factor in enabling vehicle users to compare the relative price of available fuel in the local market. Determining the consumer cost of DME is tough because it depends on raw material costs and production methods. The cost of DME is approximately 75-90% of the LPG price [Stepanenko and Kneba 2019]. Moreover, the fuel supply infrastructure must be enhanced to make DME fuel more popular [Park and Lee 2014].

6. Prospects of DME

The application of DME for transport vehicles has the potential to overcome the shortage of fossil fuel because DME is a fuel that can be produced synthetically. DME can be indigenously produced from biomass, MSW, and other renewable feed stocks and can be an attractive alternative fuel solution considering energy sustainability and environmental challenges. DME vehicles are already in use in some countries of the world. Many original equipment manufacturers (OEMs) have been working on DME-fueled vehicles for the last 20 years. Volvo (Sweden) developed the first DME bus in 1999. Caterpillar developed DME-fueled buses in 2001. Volvo Group developed a second-generation DME vehicle in 2005. The same year, Japan Oil, Gas and Metals National Corporation (JOGMEC) developed a medium-duty DME-fuelled truck. In the same year, Shanghai Coking & Chemical Corporation developed a DME-fuelled bus with mechanical fuel injection [Park and Lee 2014]. Recently, in India, IIT Kanpur and Tractors and Farm Equipment Limited (TMTL), Alwar developed a DME-fuelled tractor prototype [Agarwal et al. 2023]. Storage and distribution infrastructure needs to be developed for large-scale implementation of DME. DME has certain properties that are different from LPG, but it can be offloaded and stored at refilling stations by adopting the same methods and equipment as LPG/CNG and redesigning the LPG infrastructure [Stepanenko and Kneba 2019]. DME has physical properties similar to LPG, such as vapor pressure and existence as a gas at normal room temperature conditions; therefore, existing LPG infrastructure for storage and in-land refilling, and over-seas transportation can be used for DME with minor modifications in the pump gaskets, regulators, and seals. Since there are numerous LPG refilling stations, using these can be less costly than developing new refilling stations for DME. However, as the demand increases, new infrastructure can also be developed for DME [Semelsberger et al. 2006]. The capital investment, including the cost of production plants and infrastructure for DME, was estimated at US$ 4 billion, while it was US$ 18 billion for hydrogen, US$ 4 billion for methanol, and US$ 5 billion for ethanol [Ahrenfeldt et al. 2011]. Baena-Moreno et al. [2021] studied the economic viability of the production of DME from biogas. They concluded that the production of DME from methanol derived from biogas had a high carbon footprint that would be quite unacceptable in a carbon-neutral society. In another study, Uddin et al. [2020] investigated the techno-economic analysis (TEA) of DME from methanol dehydration. For this, methanol was derived from the bi-reforming of methane (CH_4), water, and carbon dioxide (CO_2). Also, the CO_2 was taken from two different sources: an ammonia production facility and landfill gas. They reported an estimated minimum fuel-selling price (MFSP) of $0.87/gal and $0.91/gal for both sources. The equivalent diesel price ranged from $1.63/gal to $1.70/gal. Therefore, they concluded that this method of DME production was economically viable. Grové et al. [2018] investigated the economic feasibility of DME derived from municipal solid waste (MSW) in the form of refuse-derived fuel (RDF) for its use as a cooking fuel. DME was derived from two different blends; the first was from a 50% RDF-coal blend, and the second was a 25% RDF-coal blend. They estimated the Indian basket oil price at which the cost of DME production would break even with imported LPG at approximately $130 per barrel using the 50% RDF-coal blend and $98 per barrel using the 25% RDF-coal blend. India is highly dependent on crude oil imports. Therefore, the indigenous production of DME will reduce this dependency and lower the foreign exchange depreciation. Vehicle manufacturing companies worldwide are building and carrying out research from bench-level engine testing to modify and develop DME-fueled engines [Park and Lee 2014]. If efficient fuel delivery and storage infrastructure are developed, DME can be a viable, environmentally friendly alternative fuel [Park and Lee 2014]. The engine's efficiency is very important from the perspective of fuel cost and reducing CO_2 emissions. When using hydrocarbon fuels, it is impossible to avoid CO_2 emissions. At the most, they can be reduced with the application of after-treatment systems. Since DME has a low C/H ratio, using DME with an efficient engine theoretically provides an opportunity to reduce CO_2 by up to 30% [Œwiês et al. 2022]. With the current technology, adequate optimisation of engine operating systems-such as injection strategy- is required to reach a state of clean emissions [Stepanenko and Kneba 2019]. Since DME is a derivative of methanol, developing and commercializing DME-fuelled engines will add to NITI Aayog's 'Methanol Economy,' which aims to lessen India's dependency on crude oil imports and lower GHG emissions.

7. Summary

The summary of the present literature review is presented in the form of a table below:

Table 3: Summary of the present study

S.No.	Topic	Summary
1.	• Global Energy Scenario • Environmental and Health Implications of Pollutants • Need for Alternative Fuels	With fast-depleting fossil fuels and the hazardous pollutants that are emitted from their combustion, the research and use of cost-effective, environment-friendly, and renewable alternative fuels is of utmost importance. Among many alternative fuels, Dimethyl ether (DME) is the next-generation biofuel that is seen as a promising CI engine fuel.
2.	• Dimethyl Ether (DME) • Physicochemical Properties of DME • Production and Use of DME • Safety Aspects of DME	The physical and chemical properties of DME are mentioned in Table 1. DME can be produced from both renewable and renewable feedstocks. DME-fueled vehicles are already in use in some countries.DME is a non-hazardous and environmentally friendly fuel. However, care needs to be taken during its handling.
3.	• DME as an Alternate Engine Fuel • Spray Characteristics of DME • DME Storage and Handling • Fuel Injection Equipment (FIE) for DME • Combustion and Performance Characteristics of DME engines • Regulated and Unregulated Emissions of DME engines	The macroscopic and microscopic spray characteristics of DME reveal superior atomization and vaporization characteristics of DME. This helps in the proper mixing of DME spray with air and the formation of a relatively more homogenous mixture than that of diesel. DME combustion is dominated by the mixing-controlled phase. DME-fuelled engines show comparative performance on increasing the fuel supply to 1.5 times diesel due to DME's lower calorific value.DME engines have sootless/smokeless combustion. NOx emissions vary based on the engine operation conditions. The presence of an oxygen atom and the absence of a C-C bond in DME's molecular structure reduces unburnt hydrocarbon emissions.
4.	Advantages of DME over Conventional Diesel	DME has a high cetane number and other favorable properties, making it ideal for CI engine use. Unlike diesel, it can be produced indigenously from renewable feedstocks such as biomass and MSW. The DME engines emit almost 0 smoke/soot, a major problem in diesel engines. DME engines lower emissions without the need for any expensive exhaust gas after-treatment devices.
5.	Challenges of DME Engines	DME's properties, such as low lubricity, viscosity, calorific value, high vapor pressure, and compressibility, necessitate some modifications in its fuel injection equipment.
6.	Prospects of DME	DME has physical properties similar to LPG, such as vapor pressure and existence as a gas at normal room temperature conditions; therefore, existing LPG infrastructure for storage in-land refilling, and over-seas transportation can be used for DME with minor modifications in the pump, gaskets, regulators, and seals.If efficient fuel delivery and storage infrastructure are developed, DME can be a viable, environmentally friendly alternative fuel.

8. Conclusions

From the point of view of environmental sustainability, DME has the potential to replace depleting fossil fuels.

i. DME can be produced indigenously from renewable feedstocks like biomass, MSW, low-grade coal, and methanol.

ii. DME has superior properties than conventional diesel fuel, such as a high cetane number, high oxygen content, no direct C-C bonds, low C/H ratio, low boiling point, and low self-ignition temperature. Furthermore, the spray studies have displayed DME's superior atomisation characteristics, which play an important role in air-fuel mixing in the combustion chamber.

iii. Technically, DME has physical properties similar to LPG. Therefore, LPG's infrastructure can be used for DME's handling, supply, and storage systems.

iv. However, DME has some challenges, such as its high vapour pressure, low lubricity, low viscosity, and lower calorific value than diesel, necessitating modifications in its fuel injection system.

v. Once the DME-dedicated FIS is developed, DME-fuelled engines display similar power output and reduced emissions than diesel. Because of the high oxygen content of DME and lack of direct C-C bonds, DME combustion is almost soot-free. Visibly, there is no smoke from the exhaust of DME-fuelled engines.

vi. DME can also be blended well with many hydrocarbon fuels.

vii. The blended fuels operate perfectly in CI engines without modifying the fuel supply system.

viii. More research is needed to develop efficient and cost-effective DME-fueled engines. The availability of infrastructure and distribution network of the fuel will also largely determine the commercialisation of DME fuelled vehicles in the near future.

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