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Impact of Di-Methyl Ether (DME) As an Additive Fuel for Compression Ignition Engine in Reduction of Urban Air Pollution

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ABSTRACT: With ever growing concerns on environmental pollution, energy security and future oil supplies, the global community is seeking nonpetroleum based alternative fuels to increase the efficiency of energy use. Di-methyl ether (DME) can be used as a clean, high-efficiency compression ignition (CI) engine fuel with reduced NOx, SOx, and particulate matter. DME's diesel engine-compatible properties are its high cetane number and low auto-ignition temperature. However, physical properties of DME (viz. lower viscosity, lubricity, combustion enthalpy and boiling point)demands modifications to diesel engine internal structures and components.The technology with pure DME as an alternative fuel for CI engine and vehicle is still under development stage. However, if DME is used as an additive fuel with diesel, the relative "goodness" of each fuel might be utilized. This paper analyses the potential benefit of blending DME in diesel fuel in reduction of urban air pollution.

KEYWORDS: Alternative fuel, CI engine, DME, air pollution.

I. INTRODUCTION

Transport fuel supply today, in particular to the road sector, is dominated by oil, which has proven reserves that are expected to last around 40 years. The combustion of mineral oil derived fuels gives rise to particulate matter, SOx, NOx, CO and HC emissions. Vehicular emissions are of particular concerns, since these are ground level sources and hence have the maximum impact on the general population. The rapid increase in urban population have resulted in unplanned urban development, increase in consumption patterns and higher demands for transport and energy sources, which all lead to automobile pollution.Despite the fact that the fuel efficiency of new vehicles has been improving, so that these emit significantly less emissions from transport sector the problem of air pollution has assumed serious proportions in some of the major metropolitan cities of the world and vehicular emissions have been identified as one of the major contributors in the deteriorating air quality in these urban centers.

With economic growth, demand for road transport is expected to grow dramatically. Rising incomes, combined with growing propensity for personal mobility will lead to pronounced increase in automobile ownership. As per the estimates ofInternational Energy Agency (IEA, 2004)global demand for mobility will grow rapidly with the number of vehicles projected to triple by the year 2050.In India, the number of motor vehicles has grown from 0.3 million in 1951 to approximately 128 million in 2010 which is about 425 times higher than 1951 level. During the last two decades the number of vehicles has grown by at an average rate of 10% per year (MoRTH, 2012).

Global and urban environmental problems are caused by the rapid increase of harmful exhaust emissions due to the burning of fossil fuels. Available oil deposits are calculated to last only limited years, so global community seek an urgent need for an environmentally safe and renewable new kind of alternative fuelfor improvement of the security of energy supply. Alternative fuels such as electricity, hydrogen, biofuels, synthetic fuels, methane or LPG will gradually

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become a much more significant part of the energy mix. There is rather broad agreement that all sustainablefuels will be needed to resolve the expected supply-demand tensions as well as to meet the future fuel emission standards.

Since, DME has the good thermo–chemical characteristics and can be manufactured at a low cost, it has been considered as a promising alternative fuel for compression-ignition (CI) engines.DME is considered as efficient alternative fuel for use in a diesel engine, with almost smoke-free combustion. DME has the highest wellto-wheel efficiencies of all non-petroleum based fuels except natural gas (Semelsberger et al., 2006). DMEcan meet ultra low emission vehicle (ULEV) limits for nitrogen oxides (NOx).Using existing engine technology, dimethyl ether producesthe least amount of well-to-wheel greenhouse gas emissionscompared to other alternative fuel viz. FT diesel, FT naptha, biodiesel, bionaptha,methanol, methane, and ethanol.

DME (CH_3–O–CH_3) can be produced from a variety of feed-stock such as natural gas, crude oil, residual oil, coal, waste products and bio-mass. However, the low viscosity of DME causes leakage and wear problem in injector. Another unsatisfactory property of DME is due to lower calorific value it will require higher fuel volume compared to diesel fuel. The low boiling point of DME would also demand a pressurized system to maintain the liquid state of the fuel. Practically, the addition of DME to diesels to reduce engine emissions without engine modification seems to be a more attractive proposition(Bo et al., 2006).

II. IMPACT OF VEHICULAR EMISSIONS ON URBAN AIR QUALITY

Air pollution from motor vehicles is one of the most serious and rapidly growing problems in many urban centers of the world (UNEP, 2002). While like many other parts of the world, air pollution from motor vehicles is one of the most serious and rapidly growing problems in urban centers of India (CPCB, 2006), too. The major air pollutants released as vehicle/fuel emissions are carbon monoxide, nitrogen oxides, NMVOC, methane, particulate matter, hydrocarbon, oxides of sulphur and carbon di-oxide. While the predominant pollutants in petrol/gasoline driven vehicles are hydrocarbons and carbon monoxide, the predominant pollutants from the diesel based vehicles are oxides of nitrogen. Vehicles in major metropolitan cities are estimated to account for 70% of CO, 50% of HC, 30-40% of NOx, 30% of SPM and 10% of SO_2 of the total pollution load of these cities (CPCB, 2010). The estimated pollution load from transport sector in four major metropolitan cities of India has been presented in Table I.

Table I: Estimated Pollution Load in the cities (2002)

City	Pollution Load in Metric tones per day			
	CO	NOx	HC	PM
Delhi	421.8	110.5	184.37	12.77
Mumbai	189.5	46.4	89.93	10.58
Kolkata	137.5	54.1	47.63	10.80
Chennai	177.0	27.3	95.64	7.29

Source: Auto Fuel Policy, 2002

The capital city, Delhi has the highest vehicular population in India.In Delhi, vehiculartransportis responsible for almost 70% of the total air pollution load. Percentage load contribution of different air pollutants in Delhi is shown in table II.

Table II: Pollutants load contribution from transport sector in Delhi

Pollutants	Percentage
CO	76-90 %
NOx	66-74%
SO2	5-12%
PM	3-22%

Source: Auto Fuel Policy, 2002

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III. FUEL PROPERTY DEMANDED BY A CI ENGINE

A diesel engine is referred to as a compression ignition engine. Air alone is drawn into the cylinder on the downward induction stroke of the piston. No throttling of the intake is used; therefore, for a non-turbocharged engine, the amount of air drawn into the cylinder at a certain engine speed is relatively independent of the engine output. The fuel is injected under high pressure (of order 30-100 MPa) through fine holes to form a spray of fuel droplets. This must mix with the air in the combustion chamber until the local air-fuel ratio is within flammability limits before combustion can occur. The time taken from the start of injection to the start of combustion is termed the ignition delay. The fuel property demanded by CI engine has been described below:

Energy Content: Depending on its specific composition, diesel oil has an energy content of about 36 MJ/liter. If the fuel has lower energy content than diesel the engine will need injection of relatively larger volumes of fuel, compared to diesel oil, in order to have the same power output. As a result of the lower energy content, engines running on alternative fuels will require higher (volumetric) fuel consumption and thus typical differences in vehicle design for alternative fuel in diesel engines will require larger fuel injectors, fuel pump, and fuel tank.

Lubricating Properties: The fuel system of the diesel engine, mainly the fuel injectors and fuel pump, relies on the lubricating properties of the fuel in use. If the fuel is a low lubricity fluid, then increased wear on fuel pumps and injectors have been observed. The lubrication problems can be overcome by using additives and/ or improved materials.

Cetane No: The autoignition characteristic of the diesel fuel, specified by the cetane number, is an important parameter contributing to the time taken to initiate combustion after fuel injection. A higher cetane number reduces the ignition delay and the premixed combustion.

Viscosity: Diesel fuel pumps are designed for a fuel with a higher viscosity;therefore, lower viscosity fuels can causepumping problems. Lubricating properties are affected negatively, and leakage problems might also occur with low viscous fuels. Fuel spray characteristics are also changed due to lower viscosity of fuels.

Vapor Pressure: If the fuel has higher vapour pressure, it will evaporate more readily. With the high vapor pressure in combination with a low viscosity can cause vapor locks and cavitations inside the fuel system, resulting in too little fuel being delivered to the engine.

IV. MATERIAL AND METHODS

In recent days, diesel emissions in urban areas are of most concern. Road transport is the dominant freight mode, with very little urban freight traveling by rail. The magnitude of contribution from each of the emission sources that contribute to the urban air pollution depends upon the individual emission rates and the activity level. The vehicle emission inventory can be summarized as the product of an emission rate (e.g. gram/km) and the associated vehicle activity (e.g. km/day). Diesel is used in public passenger and cargo vehicles. For estimation of emission from transport sector, 'bottom–up' approach was adopted for estimation of gaseous and particulate emission based on annual average utilization for different vehicle category, number of registered vehicles and the corresponding emission factors. Emission factor of road transport based on type of vehicle was compiled from draft report on 'Emission factor development for Indian Vehicles" (ARAI, 2008) whereas average vehicle km travel by different vehicle is taken from CPCB, 2001.

To calculate the emission from road transport following formula was used:

$$Ea = \Sigma (n_b \text{ X } K_b) \text{ X } EF_{a,b,km} \quad (1)$$

E_a = Emission of Pollutant (a)
n_b = Number of vehicles per type (b)
K_b= Annual kilometers travelled per vehicle type (b)

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$EF_{a,b,km}$ = Emission factor of pollutant (a), vehicular type (b) per driven km.

V. RESULTS AND DISCUSSION

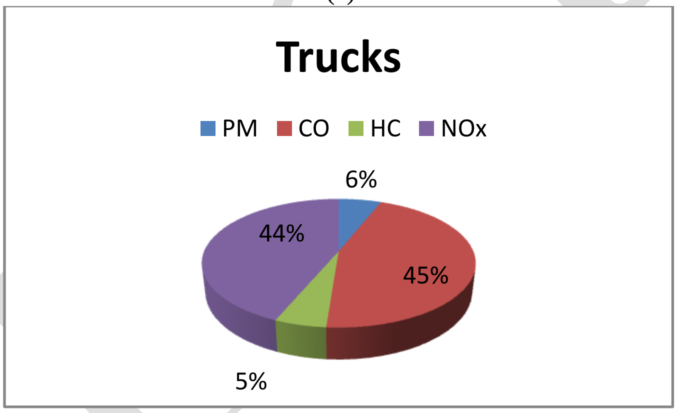
The estimated pollution load (MT/day) from buses, trucks and other vehicles for the year 2010 have been shown in Table III.

Table III: Pollutants load contribution from diesel vehicle for the year 2010.

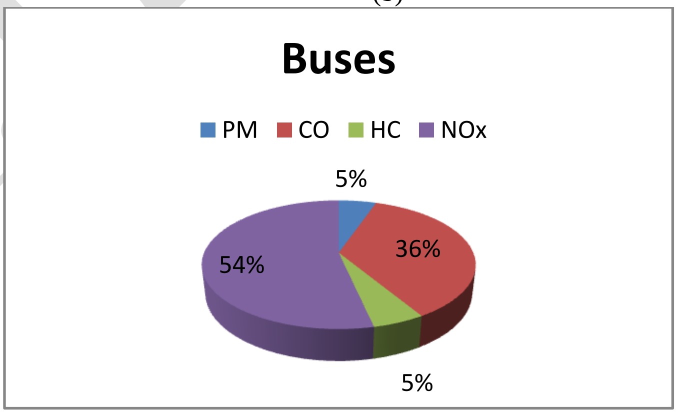
Vehicle	PM	CO	HC	NOx
Trucks	8173.2	61398.5	6999.2	59296.2
Buses	2421.3	16420.8	2380.9	24354.8
others	3551.5	34085.6	10639.5	29304.2
total	14146	111904.9	20019.6	112955.2

The pollutants of most concern from diesel vehicles are NOxand CO (figure I,a,b,c). The quantity of air pollutants emitted by the different categories of vehicles is directly proportional to the average distance traveled by each type of vehicles, number of vehicles plying on the roads, and type of fuel being used. Among the three types of diesel vehicles considered truck is found to be most polluting one.

(a)



(b)



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(c)

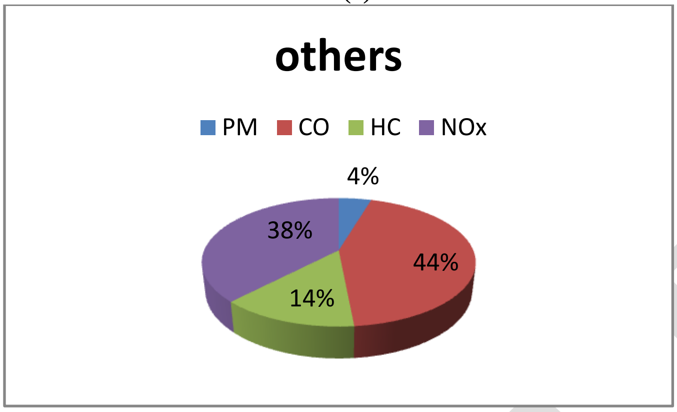

Figure I: Emission characteristics of diesel run vehicles (a) trucks, (b) Buses, (c) Others)

VI. DME ADVANTAGES

DME has a high cetane number which is appropriate for auto-ignition.DME has no carbon–carbon bond and has high oxygen content which significantly reduces smoke formation from combustion.The engine combustion noise is lower than that of diesel engine and DME can be made from various resources, such as coal, natural gas etc. The various advantages of DME as an alternative fuel for CI engine can be summarized as follows:

(i) **High oxygen content**: DME contains 35% by weight oxygen (Ying et al., 2008). Together with the absence of any C–C bonds it is responsible for its smokeless combustion, low formation and high oxidation rates of particulates.

(ii) **High cetane number**: DME has a high cetane number (N55) in comparison to diesel (40-50) fuel which results in low auto-ignition temperature and almost instantaneous vapourization.

(iii) **Low boiling point**: Low boiling point (-25°C)leads to quick evaporation when a liquid-phase DME spray is injected into the engine cylinder.

(iv) **Low injection pressure:** DME gasifies immediately during injection, due to its low boiling point, even though it is injected as a liquid. Therefore, the high fuel injection pressures, such as 50–150 MPa, used in modern diesel injection systems are not required for DME.

VII.DME DISADVANTAGES

The most challenging aspects of a DME engine are related to its physical properties and not to its combustion characteristics. Lower viscosity causes leakage from the fuel supply system. There are also lubrication issues with DME; resulting in premature wear and eventual failure of pumps and fuel injectors. The disadvantages with DME fuel has been highlighted below:

(i) **Low combustion enthalpy**: The low calorific value of DME is only 64.7% of that of diesel (Ying et al., 2008), which necessitates a larger injected volume and longer injection period for DME in order to deliver the same amount of energy to that provided by diesel.

(ii) **Low viscosity**: The viscosity of DME is lower than that of diesel by a factor of about 20; causing an increased amount of leakage in pumps and fuel injectors.

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(iii) **Low Boiling point:**Due to the low boiling point of DME (248 K), it is a gas under standard atmospheric conditions and therefore must be pressurized in a fuel system, including a storage tank, and handled like a liquefied gas. Thus, the low boiling point of DME necessitates a closed pressurized fuel system. The vapour pressure of DME, roughly the same as LPG, demands the same kind of handling and storage considerations as for LPG.

(iv) **Leakage**: Due to its low viscosity, currently available fuel-injection systems are not suitable for DME due to leakage problems. Even at atmospheric conditions the leakage of DME can be significant in regions of small clearance such as between the plunger and barrel of a rotary-type fuel-injection system. In heavy-duty engines, leakage along the plungers is more serious than in light-duty engines.

(v) **Low lubricity**: The lower lubricity of DME than that of diesel fuel leads to wear problems.

(vi) **Long injection period:** The low liquid density and low calorific value require a higher volume of DME to be injected into the cylinder, compared with that for diesel fuel. In particular, 1.8 times the volume of diesel fuel is needed (to supply the same amount of energy) which necessitates a longer injection period and advanced injection timing.

(vii) **Sealing material:** DME is not compatible with most elastomers and can chemically attack some commonly used sealing materials and other plastic components, raising questions about the durability of injection systems handling DME. A careful selection of sealing materials is necessary to prevent deterioration after prolonged exposure to DME. Sealing of DME-filled storage vessels and supply lines can, for example, be achieved with PTFE.

VIII. DME PRODUCTION

DME can be produced from carbonaceous feedstock, both from fossil fuels like natural gas and renewable sources like wood. DME production methods are of the following types:

(a) De-hydrogenation of methanol

(b) Direct conversion from synthesis gas (syngas).

Currently, most DME is produced by de-hydrogenation of methanol:

• Methanol synthesis:

$CO + 2H_2 = CH_3OH$

• Methanol dehydration:

$2CH_3OH = CH_3OCH_3 + H_2O$

The direct conversion method is the simultaneous production of DME and methanol from syngas using appropriate catalysts. The first step of direct DME production is the conversion of the feedstock to syngas, most common by steam reforming of natural gas and for coal, oil residues and bio-mass by partial oxidation through gasification with pure oxygen. The second step for the direct route is via methanol synthesis using a copper-based catalyst while the third step is the de-hydrogenation of methanol to DME using alumina- or zeolite-based catalysts. However, from both the cost and product-yield points of view, the synthesis of DME directly from syngas is considered as the preferred route for large scale production (Himabindu et al., 2010).Although it is possible to produce DME from both fossil and renewable sources; however, producing DME from fossil sources is the most viable route at present from a cost perspective(Lee et al., 2009).

IX. EMISSION CHARACTERISTICS WITH DME AS AN ADDITIVE FUEL

Many researchers have demonstrated that DME can achieve ultra-low emissions. Its exhaust gas reactivity is also very low. The environmental potential of DME as an alternative fuel is summarized below:

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Particulate matter (PM): It is well known that soot is formed in fuel-rich regions under high temperature conditions. The precursors of soot are unsaturated hydrocarbons such as acetylene (C_2H_2), ethylene (C_2H_4), and propargyl (C_3H_3), found in diesel combustion products. The proportion of fuel carbon forming soot precursors has been found to decrease with increased oxygen content in the fuel and with decreased number of C–C bonds. The soot formation is almost zero in DME combustion.

NOx: Comparative values of NOx emissions from DME CI engines and those from diesel fuel seem to vary depending on the engine conditions and the fuel supply system. NOx was found to be lower with DME than with diesel fuel which is attributed to the shorter ignition delay for DME than for diesel, the smaller amount of fuel injected during the ignition delay period and the smaller amount of fuel burned during the pre-mixed burning phase. However, it is possible that higher NOx can be produced from DME than from diesel fuel for an early start of injection since the duration of the peak combustion temperature would be longer in the initial combustion period due to the shorter ignition delay of DME.

HC and CO: The low C/H ratio, the lack of C–C bonds and the high oxygen content of the fuel give faster and more effective oxidation of intermediate species. As a result HC and CO emission are reduced.

HC emissions from DME are usually lower than or equal to those from the combustion of diesel fuel; HC emissions consist of partially or completely unburned fuel, produced in locations where combustion takes place under fuel-rich conditions, due to incomplete air-fuel mixing. Since DME has a short ignition delay period, the over rich and over-lean mixture regions formed during the ignition delay period might be smaller, resulting in significantly reduced HC emissions. Moreover, DME is an oxygenated fuel containing 35% by mass of oxygen, has good mixing characteristics resulting in reduced HC emissions.

The data of CO emissions show some contradictions depending on operating conditions. DME has good mixing characteristics, so that the locations of the fuel-rich regions in the combustion period could be reduced, resulting in lower CO emissions. The higher CO emissions sometimes associated with DME result from the longer injection duration, coupled with lower injection pressures and larger spray holes. Since there is production of CHO and CH_2O involved in the combustion of DME, depending on the reaction process, a larger amount of CO is expected to be produced compared with diesel fuel.

Non-regulated exhaust emissions: It is likely that some formaldehyde (CH_2O) is formed during combustion of DME in a CI engine, but significant emissions of sulfur dioxide (SO_2), polycyclic aromatic hydrocarbons (PAH) and benzene, toluene and xylene (BTX) are expected.

X. CONCLUSION

Numerous investigations of DME-fuelled engines have indicated that it offers excellent promise as an alternative fuel for compression-ignition operation in the automotive sector. DME is a liquefied gas that can be produced from a variety of feed stock, is non-toxic and environmentally benign. DME is as easy to handle as LPG since it is condensed by pressurizing above 0.5 MPa. DME's main feature as an efficient alternative fuel for use in compression-ignition engines is its high cetane number. The fast evaporation of DME can lead to better mixing with air in the engine cylinder and its high oxygen content can achieve smokeless combustion through low formation and high oxidation rates of particulates. However, in order to achieve an equivalent driving range as that of a diesel fuel, a DME fuel storage tank must be twice the size of a conventional diesel fuel tank due to the lower energy density of DME compared with diesel fuel. DME-fuelled systems also need lubricity-enhancing additives and anti-corrosive sealing materials to secure leakage-free operation. Moreover, it is argued that the well-to-wheels energy efficiency and CO_2 emissions for DME produced from natural gas are not better than for most other fuels, as a result of the high fuel production energy and relevant CO_2 emissions, and that diesel fuel has the highest well-to-wheels energy efficiency. Nevertheless, DME has the advantage that it can be produced from both fossil and renewable resources.

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Current transportation fuels are based on petroleum, a resource that is being depleted, and whose importation has political and societal ramifications. The infrastructure of dimethyl ether is less cost intensivethan that for hydrogen because dimethyl ether can use theexisting LPG and natural gas infrastructures for transportand storage.DME can be introduced and exploited with existing technologies, such as fuel cells. Because dimethyl ether is produced from natural gas, coal, or biomass, dimethyl ether can increase the energy security of the country.

Vehicular pollution is based on the quality and quantity of the fuel.The need to improve the security of the energy supply and to reduce theemissions of pollutant gases has led the many countries to propose theintroduction of alternative fuels in the road transport sector. The DME spray characteristics and combustion process have been investigated for various fuel-injection equipments, in a variety of prototype engines with occasional slight modifications. These engine tests with DME proved its potential as a clean alternative fuel achieving smoke-free high power operation provided optimized fuel injection equipment and the engine configuration are closely matched to reduce fuel consumption and exhaust emissions. Optimisation of the fuel injection equipment, overcoming the problem of low density, low lubricity and corrosiveness are recognized as technological barriers for mass production of the DME-fuelled compression-ignition engines. However, use of DME as an additive fuel with diesel fuel satisfies the requirement of environmentally safe and renewable new kind of alternative fuel.

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