Implementation of DME in a Small Direct Injection Diesel Engine

Kanit Wattanavichien

Internal Combustion Engine Research Laboratory, Department of Mechanical Engineering,
Faculty of Engineering, Chulalongkorn University, Bangkok 10330, Thailand
Tel: 02 218 6627 Fax: 02 252 2889 * Corresponding author: wkanit@chula.ac.th

Abstract

A small direct injection (DI) diesel engine for dimethyl ether (DME) has been developed and evaluated, first time in Thailand, by the author. The paper reports DME properties and engine conversion requirements. In addition, the investigating results of using DME as an alternative fuel candidate for diesel engine by measuring primary engine performance and black smoke characteristics were discussed. The engine measurements with this fuel were compared with those obtained by using conventional diesel fuel.

Keywords— Direct injection diesel engine; DME; Engine performance

1. Introduction

A compression ignition (CI) engine is widely used as a prime mover in variety of applications. Because of its originally high efficiency, easy operability, and high level of safety, diesel engine plays an important role in supporting human lives. However, due to its generated emission substances, PM and NOx that make serious environmental problem, the diesel engine has come to be a focus of attention with regard to the issue of CO2 that has been noticed as a growing target to be reduced. Therefore, society is now demanding more tightening in emission requirements. The demands to operate diesel engines with clean exhaust while continuing to maintain high levels of efficiency have introduced Dimethyl Ether (DME) that has been nominated as a potential alternative fuel due to no carbon-carbon bond and oxygen-contents [1-3]. It has been discovered that neat DME has a very high cetane number making DME a very attractive ideal diesel fuel substitute for diesel engines where ultra-low emissions are necessary and desirable.

DME is manufactured today by dehydration from methanol with the primary market in the aerosol industry as a replacement for chlorofluorcarbons. DME is not currently produced in sufficient quantities to support its use as a diesel fuel substitute. Furthermore, DME can be produced from a variety of feedstock including natural gas and biomass. A study of DME produced from natural gas and used as diesel engine fuel shows that the well to wheel emissions of greenhouse gases are similar for DME and diesel oil [4]. In Thailand, the thermo-chemical technology to convert biomass waste feedstock to DME and economics for constructing large scale production facilities are being considered. These wastes include agricultural residues, forestry residues, food residues from food processing, weeds, and municipal solid waste (MSW).

Economic analyses for DME's applications are subject to many factors including feedstock prices. Under the most probable scenarios, DME will cost less than diesel fuel or gasoline on an energy equivalent basis, it is also less than methanol, ethanol, or esterified bio-oils. DME economics are expected be similar to CNG or LNG, when large scale plants are considered. Since operation on DME can retain the high thermodynamic efficiency of the diesel cycle and can be accomplished without major engine changes, end user economics could be favorable for DME comparing the costs to convert diesel engines to run on spark-ignition alternative fuels. These include trucks, buses, passenger cars, agricultural tractors, and construction machinery. In addition, larger diesel engines used in railroad locomotives, generators and marine applications could also use DME to significantly lower their exhaust emissions.

Local DME production for a diesel fuel substitute was expected, the potential of using DME as a fuel in a CI engine has been investigated in this study. A demonstration model for modifying a DI diesel engine to use DME fuel has been developed and evaluated by determining the output, fuel consumption, and exhaust black smoke of the demonstrated engine using DME as a fuel.

2. Dimethyl Ether and its characteristics

DME, the simplest ether compound, is a no C-C bond, oxygenated fuel (the chemical structure of DME is CH_3-O-CH_3). It has been used as an aerosol propellant for over 60 years. Several investigations have shown that DME has a low order of acute and chronic toxicity and no mutagenic, teratogenic, or carcinogenic behavior [5-7]. Main advantages of the DME are its high oxygen content (35 %) and its high cetane number (> 55) which is higher than that of diesel fuel [8, 9]. It has been adopted as an additive for ignition improvement in alcohol-fuelled engines due to its excellent auto-ignition characteristics [10-12]. This nature of DME combustion is responsible for the near-zero particulate emissions and low noise level during engine operation compared to diesel [3, 13-15]. These combustion characteristics make DME a promising alternative fuel for compression-ignition engines. Key physical and chemical properties of DME compared with diesel fuel are shown in Table 1.

DME is in gaseous phase at room temperature and pressure conditions; therefore, it requires a pressurizing system. DME also requires more compression pump work (three times that of diesel fuel, compared to the diesel, because of its higher compressibility [3, 16]. Moreover, being a low-boiling-point fluid, the viscosity of liquid DME is low (~ 1/10 that of diesel fuel) and the liquid-DME viscosity is sensitive to variations in temperature and pressure. Adoption of an additive for viscosity enhancement, to protect damage against wear and scuffing of fuel injection components, is also necessary due to the extremely low viscosity of the DME [17, 18]. The injection system modification (longer injection duration or bigger nozzle hole size) may be required to compensate lower heating value of the DME [19]. CO and HC emissions in compression ignition engine operated with DME have been noticed lower than that with diesel fuel, while the effect of DME on NOx emission has not been identified yet [2, 16, 20]. Nonetheless, EGR (Exhaust Gas Recirculation) method has been identified as an effective way to minimize NOx in DME-operated compression ignition engines [2].

At standard temperature and pressure, DME is a liquid under modest pressure. Its handling characteristics are very similar to LPG (liquified petroleum gas). Fig. 1 compares the vapor pressure characteristics of DME, propane and butane.

The energy density (kJ/kg) of DME is significantly lower than that of conventional diesel fuel. To obtain power output equal to that achieved with diesel fuel (assuming constant engine efficiency), volumetric: fuel flow must increase by a factor of 1.8 .

Table 1. Physical and chemical properties of DME and diesel. [16]

Properties	DME	Diesel
Chemical formula	CH3-O-CH3	CxHy
Mole weight / g	46.07	190-220
Boiling point / °C	-24.9	180-360
Reid vapor pressure / MPa	0.51(20°C)	-----
Liquid density / g/cm3	0.668	0.84
Liquid viscosity / cP	0.15	4.4-5.4
Low heat value / MJ/kg	28.43	42.5
Explosion limit in air / vol.%	3.4-17	0.6-6.5
Ignition temperature / °C	235	250
Cetane number	55-60	40-55
Stoichiometric air/fuel ratio / kg/kg	9.0	14.6
Latent heat of evaporation / kJ/kg	460(-20°C)	290
%wt of carbon	52.2	86
%wt of hydrogen	13.0	14
% wt of oxygen	34.8	0

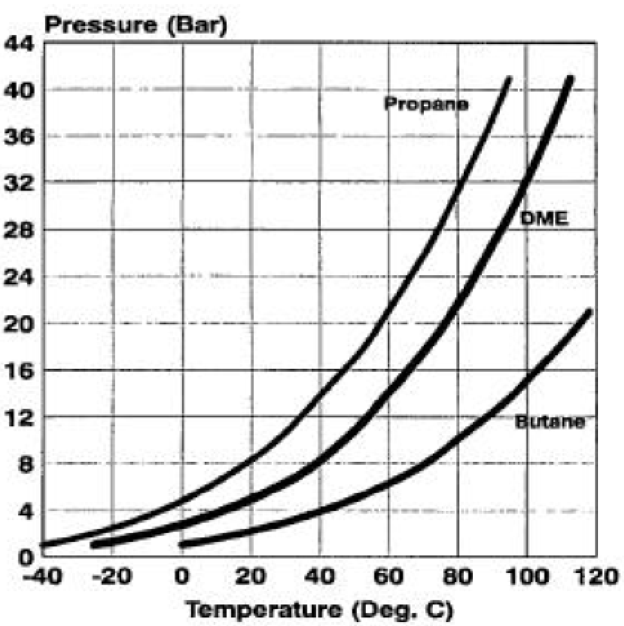


Fig 1. Vapor pressure characteristics of various fuels [8]

Cetane number, a measure of a fuel's ability to auto-ignite which has an important influence on combustion, has an important influence on diesel combustion. DME has cetane number of approximately 55-60, whereas diesel fuels have a cetane number of 40-55, making it ideal for use in diesel engines. With such high cetane number, a shortened ignition delay, lowering premixed burning and resultant NOx and noise emissions can be expected [21]. Because of its high cetane number, DME has also been used as an ignition improver on methanol fueled, compression-ignition engines [10-12].

Flame luminous characteristic, DME displays a visible blue flame, similar to natural gas, over a wide range of air/fuel ratios. This is an important safety characteristic.

DME is non-corrosive to metals and does not require special materials for fuel system structural components. Some elastomers, however, are not chemically compatible and will deteriorate after prolonged exposure to DME. Therefore, careful selection of sealing materials is necessary.

As shown in Table 1, the properties of DME can be summarized as follows:

1. DME has no C-C bonds and contains about 35% oxygen. Therefore, the combustion products, such as smoke and PM, are expected to be lower than those products from using diesel fuel. An engine with DME fuel can also tolerate more EGR rate to reduce NOx.
2. The lower heating value of DME is only 64.7% of that of diesel fuel, therefore larger amount of DME supply per cycle is needed to ensure the same engine power.
3. The cetane number of DME is higher than that of diesel fuel and other alternative fuels. Therefore, there is no need for an ignition assisted system as used for methanol, ethanol, LPG and CNG engines.
4. DME is in gaseous phase even at -20°C and ambient pressure. Its Reid vapor pressure varies with the temperature. Therefore, it has to be pressurized with pressure over 0.5 MPa to keep it in liquid phase under ambient temperature (25°C). The fuel delivery pressure should be maintained at about 3.0 MPa under engine operating conditions to prevent from vapor lock in its fuel system.
5. The latent heat of evaporation of DME is much higher than that of diesel thus mixture temperature is expected to be lower, which is beneficial to the NOx reduction.

3. DME as Fuel for IC Engine

The fuel DME for IC engine was first introduced as a starting aid for methanol S.I. engines. The low vapor pressure ensures an ignitable mixture at low temperatures [22]. Due to the high cetane number, DME has also been used as an ignition enhancer for methanol used in diesel engines [23, 24].

Since 1995, a number of research works showing the use of neat DME as fuel for diesel engines have been published [4, 13, 8, 25-32]. It has been shown that DME practically eliminates smoke emissions. DME has low boiling point (- 20^{o}C) compared to the boiling point of diesel fuel (180 – 370 ^{o}C). The lower the boiling point, the lower the soot formation, when different oxygenated fuels are compared [14].

The adiabatic flame temperature for DME is slightly lower than that for diesel fuel (represented by dodecane); thus, if the combustion conditions were identical, NOx emissions with DME are considerably lower than that with diesel oil [4, 8, 13, 25]. Kajitani et al [15] found that results from a single cylinder with a displacement of 0.6 liter engine which was operating at the recommended injection timings for conventional diesel fuel show much higher NOx emissions with DME than with diesel fuel. The higher NOx emissions than expected for DME are caused by the higher adiabatic flame temperature. The higher NOx emissions with DME can be explained by the impact of the physical properties of the fuel on injection characteristics and their influence on the injection event, spray formation, air entrainment and ignition properties. The use of a three-zone model, assuming the initial combustion takes place at φ=1, could be employed to show the effects of air entrainment. The results from the model had shown that in order to reach the measured high NOx level, the air entrainment in the DME spray must be slower than in the diesel spray. Therefore, the high local temperatures are expected to be maintained with longer period in the DME case, thus, giving higher NOx emissions despite the lower flame temperature. At the following time steps, air is mixed with the combustion products until the average φ is reached [27].

At the same timings, the energy conversion efficiency with DME was remarkably higher than with diesel fuel. Delaying the injection timing gave lower NOx emissions. The retarded injection timing with DME is more sensitive to NOx reduction than with diesel fuel while maintaining the advantage in engine fuel conversion efficiency.

It becomes apparent that soot-free combustion of the fuel is its most appealing characteristic of engine fuelled with DME. This property offsets the usual NOx – soot trade-off experienced with diesel fuel. Hence, conventional countermeasures taken to lower NOx emissions like reduced injection pressure, retarded injection, large nozzle holes etc. do not increase soot emissions. Soot- free combustion also opens the door for very high EGR rates without jeopardizing the life of the engine due to excessive wear and tear.

The ability to operate with lean mixture without black smoke makes DME compatible with most existing direct injection diesel engines. The only change of significance that is necessary is to provide a fuel injection system that will deliver adequate fuel flow and appropriate injection characteristics. Re-matching the turbocharger and the addition of an EGR system is also needed to gain the maximum benefits. A new vehicle fuel storage and supply system is, of course, also necessary. These modifications could be performed in the field, at a relatively low cost, without removing the engine from its application.

4. Fuel System Design Modifications

In this study, a small single cylinder CI engine using DME fuel was selected to verify the theory. Since dynamic injection timing, at this phase, was not determined, the injections system, injection pump, multi holes injector, the injection timing and the injection duration were kept the same as original. It was necessary to slightly modify the fuel injection system because of the special nature of the fuel. Some minor changes were made to the fuel system, only in order to facilitate satisfactory engine operation, and no attempt was made to optimize the fuel system for use with DME.

Because of the low boiling point of the fuel, it was necessary to pressurize the entire fuel system to ensure that the DME remains liquid under all operating and environmental situations and to prevent cavitation. This system contains a pressurized fuel tank, appropriate lines and valves capable of delivering the fuel at pressures of up to 30 bars. This pressure level is necessary to ensure that the fuel does not flash to vapor in the engine's fuel manifolds or fuel injection system. In initial testing, this was performed by pressurizing the tank containing DME with Nitrogen. Nitrogen was used because of its low solubility in the DME.

Another modification made to the fuel system was that the nozzle by-pass was also pressurized. Initial tests showed that there was a high rate of leakage of fuel past the nozzle plunger. This was avoided by connecting the by-pass return line to the pressurized fuel inlet to the pump. In this way, leakage of DME past the nozzle remained liquified and was returned to the inlet of the injection pump. Satisfactory operation was obtained with this arrangement.

Because of the energy density of DME, and the resultant need to inject much higher (1.8 x) volumes of fuel, it was ultimately necessary to modify the injectors to provide the necessary fuel delivery capacity. The last modification made to the fuel system was the adjustment of the nozzle opening pressure. This was due to the differences in density, compressibility and heating value of DME. For this part, baseline data with the standard injector were obtained first so that modifications to the fuel injectors could be assessed. The needle opening pressure used was considerably lower than normal for diesel operation.

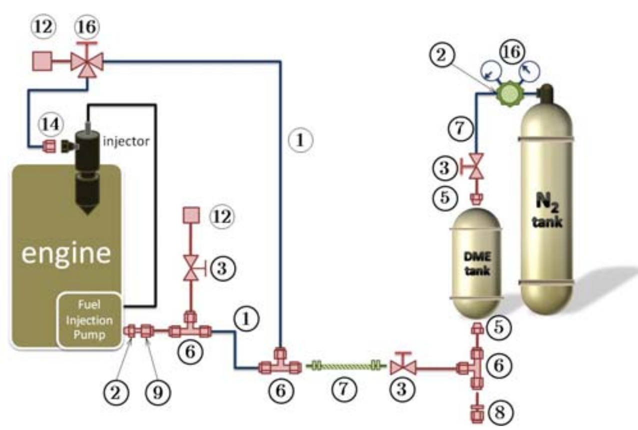
In anticipation of problems with the fuel system and other unknown effects, a small engine was chosen with the main purpose of reducing the cost of potential engine failures and replacements. In this work, a small single cylinder diesel engine (KUBOTA RT140) was selected to investigate the potential of using DME in diesel engines. The specifications of the engine and the schematic block of the fuel supply system of DME are shown in Table 2 and Fig. 2, respectively.

Table 2. Engine specifications

Engine type	Kubota RT140, single horizontal cylinder, naturally aspirated, water cooled, 4-cycle, DI
Rating output	11 kW at 2400 rpm
Maximum torque	42 N m at 1500 rpm
Bore × stroke	97 x 96 mm
Swept volume	709 cm3
Compression ratio	18:1
Fuel pump Bosch	KBAL type Injector type/injection pressure Bosch PFR M type /240 bar
Nozzle number x orifice diameter / mm	4 x 0.30
Static injection timing	25 CA bTDC
Cooling system	Radiator
Lubricant system	Forced feed

5. Adjusting the needle opening pressure for DME fuelled.

In order to cope with these DME's disadvantages - a low boiling point, low calorific value, and low viscosity but high compressibility - some modifications, such as increased pressurization and adjusting needle opening pressure, will need to be made to the fuel injection system. In this study, lowering the needle opening pressure was used to compensate the high compressibility properties of DME. It was done by means of replacing an opening pressure adjustment shim (as shown in Fig. 3). Four opening pressure adjustment shim with different thickness were selected for lowering the needle opening pressure. The injector opening pressure test results with different opening pressure adjustment shim's thickness compared with its OEM are shown in Table 3.



No	Item
1	Flexible Teflon Hose Tube Adapter
2	Male Connector
3	Ball Valve
4	Sample Cylinder
5	Tube Adapter
6	Union Tee Tube
7	Flexible Teflon Hose Tube Adapter
8	Reducer
9	Male Connector Parallel Threads
10	Gasket
11	Tube Seamless
12	Cap Tube
13	3-Way Ball Valve
14	Male Connector Parallel

Fig 2. Schematic diagram of the fuel system used to supply DME to the engine.
The pressure of the DME at the inlet to the fuel injection pump was maintained at approximately 30 bar.

Table 3 Injection pressure vs. opening pressure adjustment shim's thickness.

Opening pressure adjustment shim thickness (mm)	Injection Pressure (bar)
1.38 (OEM)	215.7
0.50	110
0.40	100
0.35	90
0.20	80

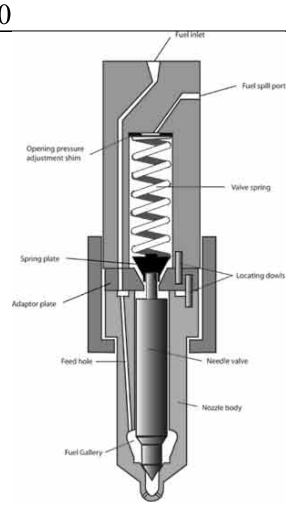


Fig 3. Injector's components

Then, each injector of different needle opening pressures, engine testing at fixed speed (1400 rev/min), and steady state with different engine loads on a dynamometer were investigated. DME consumptions of each injector's needle opening pressures were recorded. These results of DME consumption with varied engine load using four different needle opening pressures were compared with theoretical design expected and shown in Fig. 4.

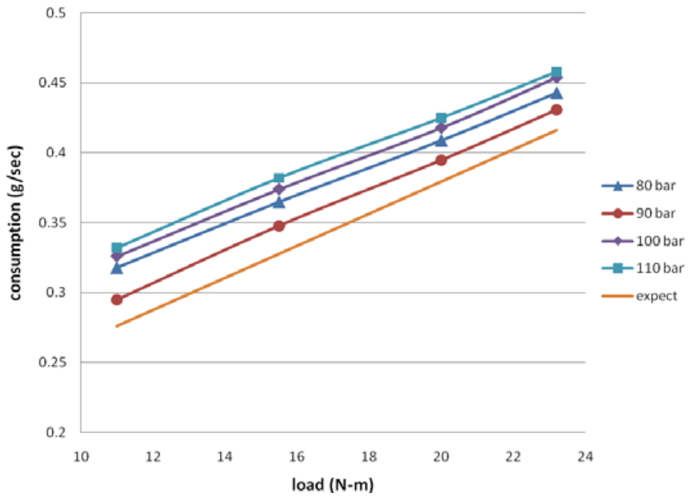


Fig 4. Comparative results between DME consumption versus engine load of four different needle opening pressures and theoretical design expected.

6. Engine Test Procedure and experimental apparatus

The experimental investigation was conducted in an IC engine laboratory. The engine was coupled with a Froude water brake dynamometer. Firstly, the engine performances and fuel consumptions at full load for DME fuelling were determined. This was conducted at constant speed, steady state condition. The engine torque was varied until the maximum value available at each test speed was attained. Then part-load performance, at selected constant engine speeds, was investigated at steady state with different selected loads (11, 15.5 and 20 Nm). The test speeds were 1400, 1700 and 2100 rpm. For each test setting point, a set of parameters for both fuelling modes was measured. Ambient pressure, humidity, engine speed, power output, exhaust back smoke and temperatures of intake air, DME consumption, cooling water, lubricant oil and exhaust gas were recorded five times for each point. The instruments used in this experiment are listed in Table 4.

It was found that the lowest DME consumption, close to theoretical design expected, was achieved with needle opening pressures of 90 bars. Therefore, in this work, a modified injector with needle opening pressures adjusted to 90 bars had been used in our developed DME engine. Then, the injector nozzle by-pass was modified as shown in Fig. 5.

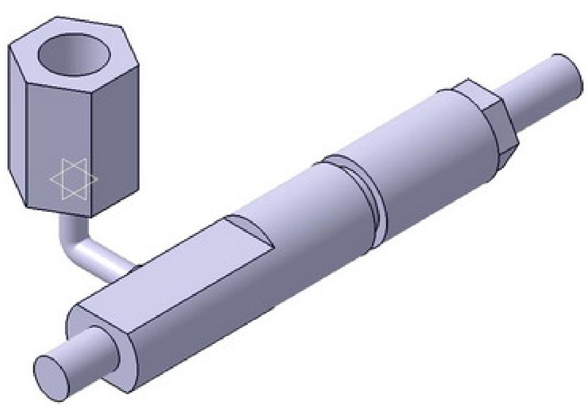


Fig 5. Return line modifications

7. Test results and discussion

At full load, the performance, DME fuel consumption and fuel conversion efficiency of the developed DME engine are presented in Fig. 6 and Table 5. Fuel conversion efficiencies with DME fuelling modes were slightly higher at all speeds. The maximum load was about 24.5 Nm at the lowest speed. The highest fuel conversion efficiency about 27.4% was observed at 1400 rpm before decreasing when the engine speed was increased. The full load performance of DME engine is about half of the output of diesel performance (as shown in Table 6), while exhaust gas temperature and exhaust black smoke are lower. This may be a result of higher heat release rate and shorter combustion duration with DME, making the in-cylinder peak pressure closer to TDC, a more effective cycle, leading to lower exhaust gas temperature, especially at lower speeds. Full load performance with DME also showed that exhaust black smoke was much less than that with diesel. The observed value which is as low as the value obtained from a full load SI engine, has confirmed that DME is environment-friendly fuel for CI engine.

The general trends of the part load engine operated with DME fuelling are shown in Table 7. It was found that the engine operated well with higher fuel conversion efficiencies and lower brake specific fuel consumptions, compared to its operation with diesel.

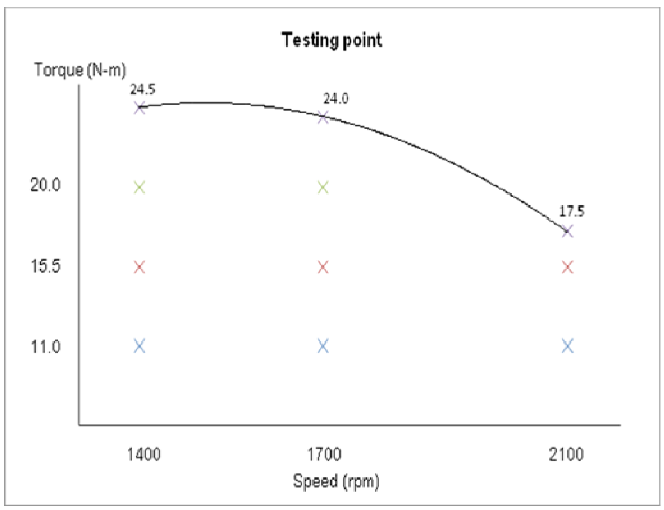


Fig 6. Full load performance of developed DME engine

8. Conclusion

A small DI diesel engine was successfully developed for DME fuel. In this study, some minor modifications were made to the fuel injection system. First, entire fuel system was pressurized. It was performed by pressuring the DME tank with nitrogen at 30 bars. Second, the nozzle by-pass was also pressurized by connecting the by-pass return line to the pressurized inlet to the pump. Finally, injector's needle opening pressure was reduced by adjustment of shim's thickness.

Table 4 Instrument specification

Measurement	Instrument	Accuracy/division
Ambient pressure	Barometer	Accuracy 0.5 mmHg/division 1 mmHg
Ambient humidity	Psychrometer	Accuracy 0.05 _C/division 0.1 ºC
Engine speed	Photodiode/transmitter	3 rev/min

Engine load	Water brake Dynamometer (arm length 0.3525 m)	Resolution 0.1 kg.
DME consumption	Balance	Resolution 2 g
Lube oil temperature	Thermal couple + transmitter	1%/division 0.1 ºC
Cooling water temperature	Thermal couple + transmitter	1%/division 0.1 ºC
Exhaust gas temperature	Thermal couple + transmitter	1%/division 0.1 ºC
Exhaust black smoke	Bosch Opacimeter DX210	Resolution 0.1 %
Ambient air temperature	Thermal couple + transmitter	0.5%/division 0.1 ºC
Air consumption		
Surge temperature	Thermal couple/transmitter	0.5%/division 0.1 ºC
Differential pressure	Orifice + inclined manometer	0.14 mmH2O/division 1 mm

Table 5 Full-load performance of DME engine

Engine speed (rpm)	Load (N-m)	Fuel conversion efficiency, %	bsfc (mg/kJ)	Exhaust temperature, °C	Exhaust Black Smoke, %
1400	24.5	27.4	475.7	235	5.3
1700	24	27.3	477.5	257	4.9
2100	17.5	22.5	578.7	255	3.7

Table 6 Full-load performance of diesel engine

Engine speed (rpm)	Load (N-m)	Fuel conversion efficiency, %	bsfc (mg/kJ)	Exhaust temperature, °C	Exhaust Black Smoke, %
1400	47.75	29.3	285	482	53
1700	47.0	30.1	278	520	40
2100	41.5	30.5	275	550	37

Table 7 Part-load performance of DME engine

Engine speed (rpm)	Load (N-m)	Fuel conversion efficiency, %		Bsfc (mg/kJ)	
		DME	Diesel	DME	Diesel
1400	11	28.2	24.6	135.1	341
	15.5	28.9	30.1	131.6	279
	20	33.7	34.0	113.1	246
1700	11	33.4	24.9	114.1	336
	15.5	36.8	29.1	103.5	287
	20	38.1	32.6	100.1	257
2100	11	34.4	23.1	126.9	362

	15.5	36.9	28.2	103.5	297

The full load performance of developed DME engine, when fuelled with DME, was about half of diesel performance. However, its exhaust black smoke was significantly as low as the value obtained from a full load SI engine. However, at part load, the developed DME engine was operated well with higher fuel conversion efficiencies and lower brake specific fuel consumptions compared with its diesel operation.

Acknowledgment

The author would like to express thanks to Prof. Fujimoto and Prof. Kajitani for their technical advices. The NEDO's grant was contributed for importing DME. The engine in this work was contributed by the Siam Kubota Industry Co. Ltd. Thanks to graduate students in the internal combustion engine research laboratory at Chulalongkorn University for their support in establishing and conducting this experiment.

References

[1]. Verbeek, R. and Van der Weide, J. (1997). *Global assessment of Dimethyl Ether comparison with other fuels*. SAE Paper 971607.
[2]. Sato, Y., Noda, A., Sakashi, T., and Goto, Y. (2000). *Performance and emission characteristics of a DI diesel operated on Dimethyl Ether applying EGR with supercharging*. SAE Paper 2000-01-1809.
[3]. Christensen, R., Sorenson, S. C., Jensen M. G., and Hansen, K. F. (1997). *Engine operation on Dimethyl Ether in a naturally aspirated, DI diesel engine*. SAE paper 971665.
[4]. Hansen, K.F., Nielsen, L., Hansen, J.B., Mikkelsen, S-E., Landälv, H., Ristola, T., Vielwerth, K. (2000). *Demonstration of a DME (Dimethyl Ether) Fueled City Bus*. SAE Paper 2000-01-2005.
[5]. Daly, J.J. Jr., Kennedy, G.L. Jr. (1987). *Dimethyl Ether: A Safety Evaluation*. Chemical Times & Trends. January.
[6]. John J. Daly, Jr., Gerald L. Kennedy, Jr., Du Pont Company. (1987). *Dimethyl Ether: A Safety Evaluation*. Chemical Times & Trends, January 1987.
[7]. John J. Daly, Jr., Dupont Company. (1982). *DME Is Now*. Chemical Times & Trends, October.
[8]. Fleisch, T., McCarthy, C., Basu, A., Udovich, C, Charbonneau, P., Slodowske, W., Mikkelsen, S.-E., and McCandless, J.C. (1995). *A New Clean Diesel Technology: Demonstration of ULEV Emissions on a Navistar Diesel Engine Fueled with Dimethyl Ether*. SAE Paper, No.950061.
[9]. Gill, D. and Ofner, H., (1999). *Dimethyl Ether –A Clean Fuel for Transportation*. SAE Paper, No.990059.
[10]. Michael E. Karpuck, TDA, Inc., Scott W. Rowley, Colorado School of Mines, (1988). *On Board Dimethyl Ether Generation to Assist Methanol Engine Cold Starting*. SAE Paper No. 881678, 1988.
[11]. Chris J. Green and Neal A. Cockshutt, Ortech International, Lionel King, Sypher, Mueller International, Inc., (1990). *Dimethyl Ether as a Methanol Ignition Improver: Substitution Requirements and Exhaust Emissions Impact*. SAE Paper No. 902155.
[12]. Michael E. Karpuck, John D. Wright, James L. Dippo, and Daniel E. Jantzen, TDA Research, Inc., (1991). *Dimethyl Ether as an Ignition Enhancer for Methanol-Fueled Diesel Engines*. SAE Paper No. 912420.

[13]. Sorenson, S.C. (1995) *Performance and Emissions of a 0.273 Liter Direct Injection Diesel Engine Fuelled with Neat Dimethyl Ether*. SAE Paper 950064.
[14]. Kajitani, S., Oguma, M., and Mori, T. (2000). 'DME fuel blends for low-emission direct-injection diesel engines', SAE Paper 2000-01-2004.
[15]. Kajitani, S., Chen, Z.L., Konno, M., Rhee, K.T. (1997). *Engine Performance and Exhaust Characteristics of Direct-Injection Diesel Engine Operated with DME*. SAE Paper 972973.
[16]. Lonbao, Z., Hewu, W., Deming J. and Zuohua, H. (1999). *Study of performance and combustion characteristics of a DME-fuelled light-duty direct-injection diesel engine*. SAE Paper 1999-01-3669.
[17]. Sorenson, S.C., Glenvig, M. and Abata, D.L. (1998). *Dimethyl Ether in diesel fuel injection system*, SAE Paper 981159, 1998.
[18]. Teng, H., McCandless, J.C. and Schneyer, J.B. (2002). *Viscosity and lubricity of (liquid) Dimethyl Ether – an alternative fuel for compression ignition engines*, SAE Paper 2002-01-0862, 2002.
[19]. Gill, D., Ofner, H., Sturman, E., Carpnter, J., and Wolvrton, A. (2001). *Production feasible DME technology for direct injection CI engines*, SAE Paper 2001-01-2015.
[20]. Anderson, O., Collin, R., Alden, M. and Egnell, R. (2000). *Quantitative imaging of equivalence ratios in DME sprays using a chemically preheated combustion vessel*. SAE Paper 2000-0-2785.
[21]. Christopher I. McCarthy, Amoco Oil Co., Warren J. Slodowske, Edward J. Sienicki, and Richard E. Jass, Navistar International Transportation Co., (1992). *Diesel Fuel Property Effects on Exhaust emissions from a Heavy Duty Diesel Engine hat Meets 1994 Emissions Requirements.* SAE Paper No. 922267.
[22]. Kozole, K.H., Wallance, J.S. (1988). *The use of Dimethyl Ether as a starting aid for methanol-fueled SI Engines at low temperature*. SAE Paper 881677.
[23]. Karpuck, M.E., Wright, J.D., Dippo, J.L., Jantzen, D.E. (1991). *Dimethyl Ether as an Ignition Enhancer for Methanol-Fueled Diesel Engine*. SAE Paper 912420.
[24]. Murayama, T., Chikahisa, T., Guo, J. (1992). *A Study of a Compression Ignition Engine with Converted Dimethyl as an Ignition Improver*. SAE Paper 922212.
[25]. Ofner, H., Gill, D.W., Krotscheck, C. (1998). *Dimethyl Ether as Fuel for CI Engines – A New Technology and Its Environmental Potential*. SAE Paper 981158.
[26]. Kapus, P., Ofner, H. (1995). *Development of a Fuel Injection Equipment and Combustion Systems for DI Diesels Operated on Dimethyl Ether*. SAE Paper 950062.
[27]. Konno, M., Katjitani, S., Oguma, M., Toshiyuki, I. Shima, K-I. (1999). *NO Emission Characteristics of a CI Engine Fueled with Neat Dimethyl Ether*. SAE Paper 1999-01-1116.
[28]. Chen, Z., Kajitani, S., Minegisi, K., Oguma, M. (1998). *Engine Performance and Exhaust Gas Characteristics of a Compression Ignition Engine Operated with DME Blended Gas Oil*. SAE Paper 982538.
[29]. Alam, M., Fujita, O., Ito, K., Kajitani, S., Oguma, M., Machida, H. (1999). *Performance of NOx Catalyst in a DI Diesel Engine Operated with Neat Dimethyl Ether*. SAE Paper 1999-01-3599.
[30]. Wakai, K., Nishida, K., Yoshizaki, T., Hiroyasu, H. (1999). *Ignition Delays of DME and Diesel Fuel Sprays injected by a D.I. Diesel Injector*. SAE Paper 1999- 01-3600.
[31]. McCandless, J.C., Teng, H., Schneyer, J.B. (2000). *Development of a Variable-Displacement, Rail- Pressure Supply Pump for Dimethyl Ether.* SAE Paper 2000-01-0687.
[32]. Ikeda, M., Mikami, M., Kojima, N. (2000). *Exhaust Emissions Characteristics of DME/Diesel Fuel Engine*. SAE Paper 2000-01-2006.