Dimethyl Ether as an Ignition Improver for Hydrous Methanol Fuelled Homogeneous Charge Compression Ignition (HCCI) Engine

M. Venkatesan, N. Shenbaga Vinayaga Moorthi, R. Karthikeyan, A. Manivannan

Abstract**—**Homogeneous Charge Compression (HCCI) Ignition technology has been around for a long time, but has recently received renewed attention and enthusiasm. This paper deals with experimental investigations of HCCI engine using hydrous methanol as a primary fuel and Dimethyl Ether (DME) as an ignition improver. A regular diesel engine has been modified to work as HCCI engine for this investigation. The hydrous methanol is inducted and DME is injected into a single cylinder engine. Hence, hydrous methanol is used with 15% water content in HCCI engine and its performance and emission behavior is documented. The auto-ignition of Methanol is enabled by DME. The quantity of DME varies with respect to the load. In this study, the experiments are conducted independently and the effect of the hydrous methanol on the engine operating limit, heat release rate and exhaust emissions at different load conditions are investigated. The investigation also proves that the Hydrous Methanol with DME operation reduces the oxides of Nitrogen and smoke to an extreme low level which is not possible by the direct injection CI engine. Therefore, it is beneficial to use hydrous methanol-DME HCCI mode while using hydrous methanol in internal Combustion Engines.

Keywords**—**Hydrous Methanol, Dimethyl ether, Performance, Emission and Combustion**.**

I. Introduction

HOMOGENEOUS Charge Compression Ignition (HCCI) engine is a potentially attractive operating mode of internal combustion engines. It combines the advantages of both SI and CI engines. HCCI engine has an ability to fire all kinds of fuel irrespective of its octane and cetane number by compression ignition and it has a large potential to reduce NO and smoke emissions.

Methanol which is commonly known as wood alcohol contains one carbon atom per molecule. Methanol is an often used industrial chemical for more than three decades. It is produced from steam-reformed natural gas and carbon dioxide using a copper based catalyst. Currently, methanol is used as a feed stock for a variety of commonly used organic chemicals, including formaldehyde, acetic acid, chloromethane, and methyl tertiary butyl ether. Table I shows the properties of hydrous methanol. Dual – fuel mode of operation is a feasible way of using biogas in CI engines with diesel as a secondary fuel [1], [2]. But, dual fuel mode emits more HC and CO emissions with lower brake thermal efficiency. However, it is observed that smoke and NO_x emissions are lower compared to the conventional CI mode.

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TABLE I
PROPERTIES AND COMPOSITION OF HYDROUS METHANOL

Chemical Structure	CH_3OH
Fuel Material	Natural gas, Coal or Woody Biomass
Physical State	Liquid
Molecular Weight	32.04
Pump Octane Number	112
Auto Ignition Temperature	897^0F
Composition Weight %	
Carbon	37.05
Hydrogen	12.6
Oxygen	49.9

In [3] controlled auto ignition combustion in a two stroke engine to reduce instability at part loads and they also achieved good reduction of emissions and fuel consumption. The important properties of DME are given in Table II.

TABLE II
PROPERTIES OF DME

Cetane Number	55 to 60
Density	660 Kg/m^3
Autoignition Temperature	350^oC
Calorific Value	28.4 MJ/Kg
Boiling Temperature	-25^oC
Stoichiometric air fuel ratio	9:1

In [4] applied the HCCI combustion into a four stroke engine using primary reference fuels. In [5] used a port fuel injection injector to supply diesel into the intake air stream at various inlet air temperatures and compression ratios. This resulted in early heat release during compression stroke itself, and the researchers concluded that low compression ratio is most suitable for port injected diesel fuelled HCCI engine. In [6] investigated the effect of inlet charge temperature, cool EGR, injection timings and equivalence ratio on the performance of a diesel fuelled HCCI engine and achieved comparatively higher loads by using cool EGR. In [7] studied the effect of internal and externally cooled EGR on the performance of a diesel fuelled HCCI engine. They concluded that internal EGR benefited the formation of homogeneous mixture and reduced smoke emission, whereas externally cooled EGR could help extend upper load limit of HCCI operation. In [8], [9] adopted acetylene as a fuel for HCCI engine due to its auto ignition temperature and high flammability. They used inlet charge temperature to control combustion phasing. In [10] followed a multi-dimensional Computational Fluid Dynamics (CFD) model to analyze Dimethyl Ether (DME) fuelled HCCI engine. A reduced chemical mechanism coupled with a CFD code of the multi-dimensional CFD model has been carried out in this investigation. The emissions such as unburned hydrocarbon (HC), CH_2O and CO emanates from the bottom, middle and upper part of the piston-ring crevice region respectively. In [11] found out a parallel computing multi-zone combustion model for stimulating operational characteristics of an n-butanol/n-heptane fuelled HCCI engine utilizing negative valve overlap (NVO) technology. In [12] used DME as an ignition controller in a methanol fuelled HCCI engine. In [13] experimentally proved the suitability of wet ethanol in HCCI combustion. They used inlet charge heating to control the combustion phasing.

The present work concentrates on operating a single cylinder engine in hydrous methanol fuelled HCCI mode in a wide load range by using DME as an ignition improver. In this study, it is aimed to study the effect of DME flow rate on the performance, emissions and operating load range of a hydrous methanol fuelled HCCI mode, at a constant speed of 1500 rev/min. Finally, DME mass flow rate for best brake thermal efficiency point, at each load condition is found out.

II. Experimental Setup

A single-cylinder, water-cooled, direct injection CI engine was modified to operate in a HCCI mode. A suitable eddy current dynamometer was coupled to the engine for loading and measurement purposes. The engine specifications are shown in Table III. The engine used in the test rig is a regular diesel engine. The inlet side of the engine has two electronic fuel injectors to supply hydrous methanol into the engine separately.

TABLE III
Specifications of the Engine

Make and Model	Kirloskar, AVI
General details	Four stroke, compression ignition, constant speed, vertical, air-cooled, direct injection
Number of cylinders	One
Bore	87.5 mm
Stroke	110 mm
Cubic capacity	661 cc
Compression ratio	17.5:1
Rated speed	1500 rpm
Rated output	4.4 kW@ 1500 rpm
Fuel injection timing	23^o bTDC
Diesel injector opening pressure	180 bar
Type of combustion chamber	hemispherical open combustion chamber

The inlet side of the engine also consists of anti-pulsating drum and air temperature indicator. The outlet side of the engine consists of an exhaust gas temperature indicator, gas analyzer and smoke sampler. The fuel used, Hydrous Methanol was stored in separate fuel tanks and were injected into the intake manifold using two separate electronic fuel injectors. The fuel flow rate of hydrous methanol has been measured using ECM and injector calibration curve. The injector used for hydrous methanol injection has been recalibrated before the application. The calibration curve has been prepared using amount of fuel discharge and pulse width of the pulse delivered by the ECM. The flow rate of DME has been measured using excess air ratio. A separate measuring probe has been inserted the suction side of the engine between the two injectors. This helps to measure the excess air ratio of DME supplied by the DME injector. The setup also consists of diesel consumption measuring facility. The cylinder pressure data and crank angle data were acquired by a 16 bit data acquisition system. This system analyses the combustion parameters. The schematic of the experimental setup is shown in Fig. 1.

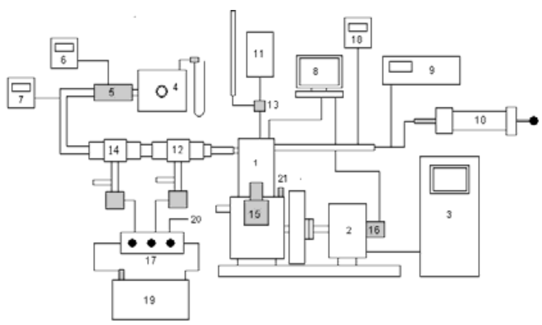

Fig. 1 Schematic of experimental setup
1. Diesel Engine, 2. Eddy current Dynamometer, 3. Dynamometer Control, 4.Anti pulsating drum, 5. Air preheater, 6. Watt meter, 7. Inlet temperature indicator, 8.Computer with DAQ, 9.Gas Analyzer, 10. Smoke sampling pump, 11. Diesel tank, 12 Hydrous Methanol injector, 13. Three way cock 14.DME Injector, 15. Fuel Injection Pump, 16. Crank angle encoder 17. ECM, 18.Exhaust gas temperature indicator, 19.Battery, 20. Input signal for ECM operation, 21. Inductive pickup for ECM operation

III. Methodology

Hydrous methanol has higher self-ignition temperature and poor cetane value and hence it is hard to auto-ignite in the HCCI engine without ignition assistance. Hence, auto-ignition assistance is mandatory for hydrous methanol application in a HCCI engine. In the investigation Dimethyl Ether (DME), a high cetane fuel has been used as an ignition improver and supplied along with methanol fuel, through separate fuel admission devices. The suction side of the engine had the facility to admit Hydrous-methanol and DME through two separate electronic fuel injectors. The quantity of DME and Hydrous methanol were measured and controlled through an Engine Control Module (ECM). The DME admitted along with methanol helped to improve its cetane number and hence, the mixture was ignited well. The quantity of DME flow rate is measured through excess air ratio and the range of excess air ratio handled in this method varied from 6 to 10. The combustion phasing, the rate of combustion and burning duration were changed by the DME flow rate.

IV. Results and Discussion

Both hydrous methanol and DME flow rates affect combustion characteristics of hydrous methanol-DME HCCI operation. In order to present their effect on engine performance and emissions, in the following discussion, hydrous methanol air ratio, and DME excess air ratio are defined as follows.

A. Operating Range

Dimethyl ether was admitted along with methanol fuel and the mixture was inducted during suction stroke. The quantity of DME varied with respect to load and the quantity of methanol used. The operating range of HCCI operation has been limited by two main factors. They are ‘knock limit’ and ‘misfire limit’. The knock limit was detected by unacceptable rate of pressure rise and the misfire limit was detected by excessive variation of Coefficient of Variation (COV). The COV was calculated using IMEP observed during 100 consecutive engine cycles. The COV is usually expressed in terms of percentage. Since the drive ability problems in automobiles normally arise when COV exceeds 10%, this value was used for fixing misfire limit in the present investigation. Fig. 2 shows the operating range of Hydrous methanol fuelled HCCI engine for various DME excess air ratios and methanol flow rates. The operating range of methanol varies with respect to load and DME flow rates. Higher loads require lower DME flow rates and lower loads require higher DME flow rates. The temperature of combustion is the main reason for the change of DME flow rates.

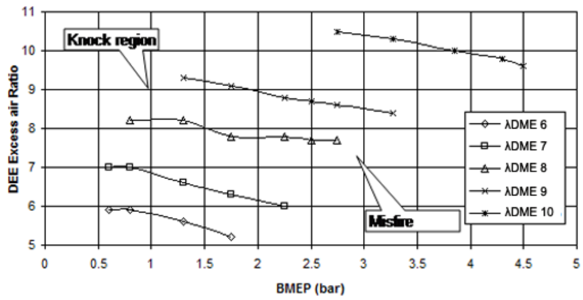

Fig. 2 Operating range of hydrous methanol HCCI engine at various DME excess air ratios

The misfire limit and knock limit at each and every DME flow rate has been identified by increasing and decreasing the methanol flow rates. During this test, the engine was kept at one particular DME flow rate. Subsequently, the methanol flow rate was increased up to the misfire limit and decreased up to the knock limit. The stable operating range obtained between the knock and misfire limit is called as the operating range of the HCCI engine at that particular DME excess air ratio.

B. Brake Thermal Efficiency

From the figure, it is seen that the brake thermal efficiency of one particular DME flow rate increases with increasing methanol flow rates and decrease due to sluggish burning and misfiring of methanol fuel. The change of methanol flow rate changes the cetane number. More specifically, at higher methanol flow rates the cetane number falls below the requirement and offered an inferior performance at higher flow rates of methanol. The increasing trend of the brake thermal efficiency observed at the beginning is due to better combustion phasing and higher cetane value of combusting mixture. The maximum brake thermal efficiency obtained at one particular DME flow rate is termed as optimum brake thermal efficiency.

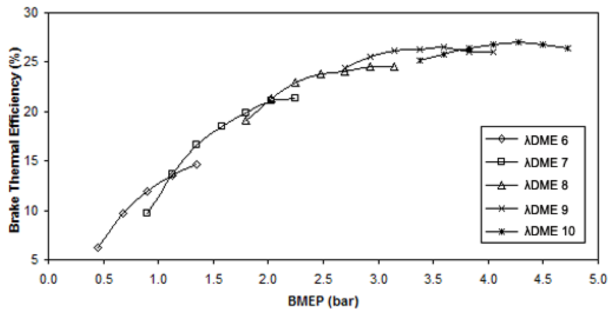

Fig. 3 Variation of Brake Thermal Efficiency at various DME excess air ratios

C. Oxides of Nitrogen Emission

NO_x emission strongly depends on local temperature. But high local temperature may have poor global combustion efficiency. In addition, the flame temperature depends on equivalence ratio and mass fraction of residual. Higher DME flow rates are used at lower BMEPs and the lower DME flow rates are used at higher BMEPs. Fig. 4 shows a variation of NO_x emissions at various DME excess air ratio and methanol flow rates. From the figure, it is found that the NO emission increases with an increase in hydrous methanol flow rate and increase in BMEP. The lower combustion temperature at lower BMEP reduced the reaction kinetics of nitrogen with oxygen and caused lower NO_x emission. This trend was reversed when the engine was offered with higher BMEP. During the higher BMEP, the temperature of combustion was higher and it increased reaction kinetics of nitrogen with oxygen and caused higher NO_x emission. At any particular DME flow rate, the increase in methanol flow rate increases NO_x emission. This was due to the increase in combustion temperature which was caused by increase of methanol flow rate and decrease of cetane number. However, the NO_x emission of methanol fuelled HCCI engine is 10 to 17 times lower than DI CI mode.

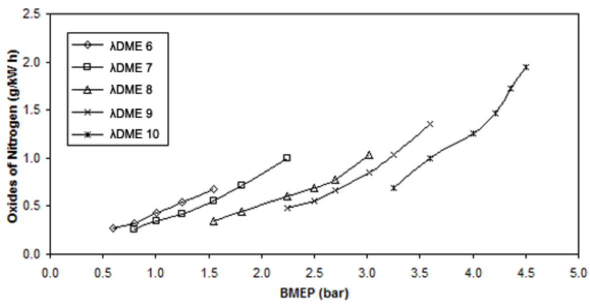

Fig. 4 Variation of Oxides of Nitrogen emission at various DME excess air ratios

D. Carbon Monoxide Emission

Carbon monoxide (CO) emission is generally an indication of incomplete oxidation of fuel. From the figure it is seen that the CO emission decreases with increase in hydrous methanol flow rate. It is also noted that the CO emission decreases with increase in BMEP. The reason for lowering of CO emission is an increase in combustion temperature that is caused due to the higher quantity of methanol utilization. The higher quantity of hydrous methanol usage increases the combustion temperature and lowers the CO emission. This is the reason for the lowering of CO emission with respect to increase in BMEP.

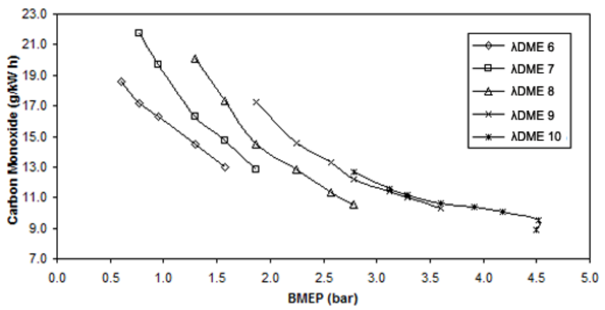

Fig.5 Variation of Carbon Monoxide emission at various DME excess air ratios

E. Unburned Hydrocarbon Emission

From the figure it can be seen that the HC emission increases with increase in methanol energy share. The reasons for the increasing trend of HC emission for one particular DME flow rate is lowering of cetane value by increasing methanol energy share. This trend is observed in all DME flow rates and hence, the HC emission increases gradually from lower to higher BMEP. In addition lower DME flow rates form weakened ignition Centre during auto-ignition. This poor ignition Centre finds it difficult in incinerating the mixture fully and causing the liberation of more HC. Higher DME flow rates from a strong ignition Centre that incinerates all the mixture without leaving HC emission. Higher DME flow rate advances the combustion timing and causes higher cylinder gas temperatures (about 1100K to 1300 K). This is the main reason for lower HC emission at higher DME flow rates. When BMEP increases the DME flow rate decreases and the hydrous methanol flow rate increases. Higher energy share of methanol increases cylinder gas temperature and lowers the DME utilization.

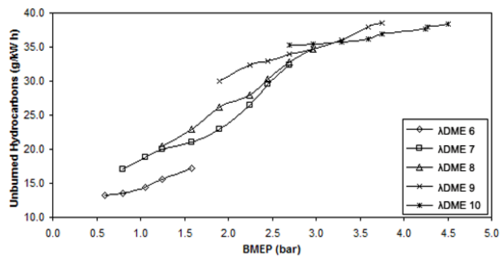

Fig. 6 Variation of Unburned Hydrocarbon emission at various DME excess air ratios

F. Maximum Rate of Pressure Rise

It is observed that the slope of the curves increases with increase in excess air ratio. This is mainly due to decrease in DME energy share and increase in methanol contribution. Since methanol has a lower cetane value, it offers a higher rate of heat release in shorter duration. This is the main reason for higher RPR at higher BMEP and at higher DME excess air ratio. The maximum rate of pressure rise offered by hydrous methanol in HCCI engine is not more than 8.5 bar per in [14]. Rate of pressure rise is an important parameter for HCCI investigation as it is used to define the upper boundary of HCCI combustion. When the fuelling rates are increased, the HCCI combustion rates increase and cause an unacceptable rise in engine noise, which may eventually lead to higher level of NO_x emission.

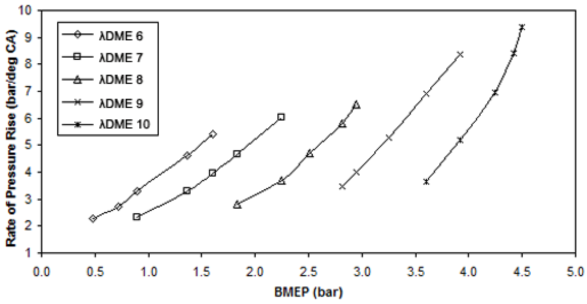

Fig.7 Variation of Rate of Pressure Rise at various DME excess air ratios

G. Cylinder Pressure Diagram and Rate of Heat Release

It can be noticed that the maximum pressure decreases when DME excess air ratio increases. This is mainly due to the change in heat release rate caused by the change in DME flow rates. The higher DME flow rates have advanced the combustion phasing and caused the rapid rate of heat release. This was the main reason for the higher cylinder pressure. This trend was reversed when the DME flow rates have been decreased. The lower DME flow rates have been retarded the combustion phasing and caused for the lower rate of heat release. This was the main reason for the lower cylinder pressure. Fig. 8 shows the rate of heat release for hydrous methanol fuelled HCCI combustion at various equivalence ratios of DME. From the figure it is seen that the highest rate of heat release occurs when rich mixture is present (lowest excess air ratio present) and the lowest rate of heat release occurs when lean mixture is present in [15]. With rich mixtures, a large amount of fuel is auto-ignited at several locations in the combustion chamber as compared to lean mixture. Hence, the rate of heat release is higher for rich mixture than lean mixture. The start of combustion advances and the low temperature reaction (LTR) increases with increase in DME flow rate. This is due to the improvement in cetane value by the addition of DME. Higher DME flow rate raises the cetane value, advances the combustion timing and increases the heat release rate. This trend reverses when DME flow rate decreases. From the experiment it is seen that the variation of DME quantity changes the rate of heat release and found that higher DME quantity performs better than that of lower DME quantity.

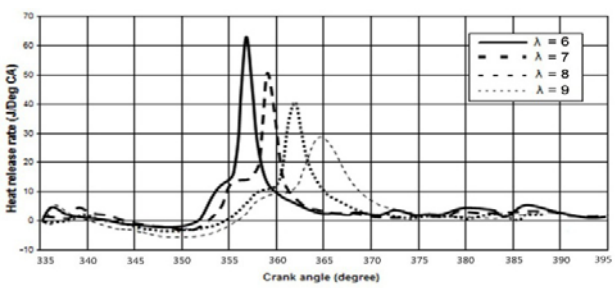

Fig. 8 Variation of heat release rate Patterns at 3 bar BMEP for various DME flow rates

V. CONCLUSION

From the detailed experimental investigation, conducted using DME assisted hydrous methanol fuelled HCCI engine, the following major conclusions are drawn.

1. Results show that DME assisted Hydrous Methanol performed well in HCCI engine after little engine modifications.
2. The water content present in the hydrous methanol helps to phase the start of combustion effectively and to change the rate of combustion.
3. The maximum Brake Thermal Efficiency obtained by this method at full load is 26% which is 4% lower than that of diesel Fuelled DI CI mode of operation.
4. The Hydrous Methanol HCCI operation also reduces NO_x and smoke emission extremely low. It is approximately 17 times lower than that of diesel fuelled DI CI mode of operation.
5. This investigation shows increased CO and HC emission which is 3% higher than that of diesel fuelled DI CI mode of operation. However, this is a Conventional behavior of HCCI operation.
6. From the above conclusion, it is found that DME assisted hydrous methanol fuelled HCCI engine reveals that the hydrous methanol of 15% of water content performed well in HCCI engine without much worsening its performance and emission behavior

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