Enabling Methanol/Diesel Dual Fuel Reactivity Controlled Compression Ignition in an Automotive Light Duty Diesel engine

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ABSTRACT

Previous research works has shown that fuel reactivity controlled compression ignition is a promising approach to breakdown the trade-off relationship between NOx and soot emissions with better thermal efficiency. However, less efforts have been dedicated to achieve dual fuel RCCI operation for entire load and speed range conditions. On other hand, higher CO and HC emissions in reactivity controlled compression ignition mode decreases the combustion efficiency. To mitigate this, an investigation on reactivity controlled compression ignition combustion has been performed using a renewable oxygenated alternative methanol fuel as a low reactivity fuel and diesel as a high reactivity fuel at different ESC cycle points. For the implementation of RCCI combustion in an on-road vehicle it is essential to understand the effect of each operating parameters on combustion and emission characteristics. Hence, in the present work, an experimental parametric study was performed by sweeping different operating parameters for a particular speed and load conditions. Later, based on the results, experiments were conducted at different ESC points and the results were compared with the conventional diesel combustion. A three-cylinder light duty diesel engine was suitably modified for this purpose and tested. Use of higher methanol percentage and EGR rate was helpful in extending the load range by reducing the maximum rate of pressure rise. The experimental results reveal that, methanol/diesel reactivity controlled compression ignition mode exhibited 80% reduction in NOx and soot emissions at tested load and speed conditions compared to conventional diesel operation which may eliminate the use of after treatment systems. However, marginally higher HC and CO emissions were observed in RCCI combustion compared to conventional operation predominantly at lower load and higher speed conditions. It can be reduced by the existing diesel oxidation catalyst system without compromising the fuel consumption. Furthermore, a maximum of 6.1% increase in brake thermal efficiency is observed in RCCI mode compared to conventional diesel combustion mode operation.

Keywords: Methanol, ESC cycle points, RCCI, NOx, Smoke

1 INTRODUCTION

An increasing environmental concerns from internal combustion engine (ICE) along with increasing usage of petroleum based fuel, demand the automotive industries and research institute to identify the pollution free ICE along with alternative fuel. Hence, nowadays a dual fuel reactivity controlled compression ignition [1] has been going on as a focus of research in the field of ICE along with utilisation of an alternative fuel to achieve zero level of pollutant emission and to avoid the use of petroleum based fuel. In this combustion strategy main emission from diesel engine such as oxides of nitrogen (NOx) and particulate matter (PM) is reduced by promoting air & fuel mixture formation and diluted in-cylinder charge [2]. In addition, in this strategy improved indicated thermal efficiency has been achieved by reduced compression work and heat losses [3]. Previous studies proved that RCCI combustion concept is a promising concept to breakdown NOx and PM trade off relation together with higher thermal efficiency [4] on different engines configuration and fuel combination. In this advanced combustion mode, the limitation of low temperature combustion has been minimized such as combustion control by adjusting the ratio between two different reactivity fuels and direct injection timing. Even though, the previous literatures show that, higher HC and CO emissions at lower loads and higher rate of pressure rise (RoPR) at higher loads [5] are the obstacles in implementing the RCCI combustion in an on-road diesel engine.

To address the above problems, various methods have been tried such as dual-mode RCCI/CDC (Switching the combustion concepts) operation [6], a lower compression ratio (<15:1) [7], optimisation of direct injection timing, spray cone angle and oxygenated alternative biofuels [8]. In addition, as per the author knowledge the previous experiments studies are done at a particular speed or load conditions only.

Considering this, in the present study an investigation is made to attempt RCCI combustion using methanol as a low reactivity fuel and diesel as a high reactivity fuel at different ESC cycle points with some modification in the stock engine system. Methanol is an alternative fuel produced from various abounded resources. In addition, methanol is a promising alternative fuel because of its higher oxygen content, lower carbon to hydrogen ratio, low production cost, already more established manufacturing plants [9]. Further, the higher latent heat of vaporization of methanol is very useful in extending the load limit with lower rate of pressure rise. In addition, unique molecular structure without C-C bonding is beneficial for RCCI combustion [10]

The objective of the present study is enabling dual fuel RCCI combustion in an automotive diesel engine using methanol and diesel fuel. The experiments were conducted at different European standard cycle (ESC) to understand methanol/diesel dual fuel RCCI combustion at all engine speed and load conditions. Finally, the obtained results were compared with conventional diesel combustion's (CDC) performance, emissions and combustion characteristics.

2. EXPERIMENTAL METHODOLOGY

2.1 EXPERIMENTAL SETUP

In the present work, all the experiments were conducted in a three cylinder, turbocharged, CRDI 1.5 L, 17.2 compression ratio diesel engine. The engine was suitably modified to enable methanol/diesel dual fuel RCCI operation. The engine was equipped with all basic measuring, controlling instruments and auxiliary facilities. Dynalac make ECB200 eddy current dynamometer with digital controller was used to control engine speed and torque. The methanol fuel was injected using methanol compatible fuel injector placed in the intake manifold. The methanol injection pressure was maintained at 4 bar using a submersible electronic feed pump and valve actuated pressure control unit. Methanol fuel line pressure was measured using calibrated pressure gauge. The direct injection diesel fuel was injected using an existing common rail direct injection system without any modification. Nira i7 open electronic control unit was used to control both methanol and direct fuel injector. The mass flow rate of methanol and diesel was measured using a Micro motion Coriolis CMF010 fuel flow meter with Agilent data logger and averaged over 2 minutes. The concentration of engine out gaseous emissions such as HC, CO, CO_2 and NO were measured by an AVL 444N Digas Analyzer. Smoke emission was measured by AVL 437_C opacity smoke meter. The in-cylinder pressure was measured using direct mounted Kistler make 6125A piezo-electric pressure transducer. The intake air and exhaust gas pressure were measured using AVL LP11DA low pressure sensor and crank angle position was obtained using Kistler 3015A optical encoder. The in-cylinder pressure and crank angle were acquired and amplified using AVL IndiSmart 512 data acquisition system. Amplified pressure signal was matched with corresponding crank angle and various combustion parameters are calculated using AVL Indicom software. The intake air flow rate was measured using existing stock hot film mass air flow sensor. The intake air, exhaust gas, coolant and oil temperatures were measured using k type thermocouples with digital indicators. During the experiments, to ensure the results are repeatable and within 95% confidence level, all the experiments conducted in this study were repeated and the uncertainty for each measured and derived parameters are estimated based on the analysis by Holman [11].

2.2 FUELS AND TEST PROCEDURE

In the present study commercially available diesel fuel in India was used as a high reactivity fuel. The 99.5% of pure analytical reagent grade methanol was used as a low reactivity fuel. The properties of fuels were tested as per standard and used for the calculation.

In the present study, the experiments were performed at three ESC cycle points of speed A (2100 rpm), B (2500 rpm) and C (3000 rpm) with 25% and 50% of full load for the respective speed conditions. To avoid discrepancy in the test results cooling water temperature was maintained at 85 °C ±1 °C and lubricating oil temperature at about 95 °C± 2°C. The boost pressure was set at 1.5 bar, 1.75 bar, 2.1 bar for low, medium, high speed condition respectively. The input energy of both CDC and RCCI combustion was equal to 28, 44, 34, 55, 44, 62 kW for 2100 rpm (36 Nm), 2100 rpm (71Nm), 2500 rpm (35 Nm), 2500 rpm (70 Nm), 3000 rpm (27 Nm) and 3000 rpm (67 Nm) respectively. Initially, test engine was fired under CDC combustion and after the warm up, operation was shifted to RCCI mode of operation by introducing methanol in the intake manifold and diesel fuel directly into the cylinder by common rail direct injection. To obtain optimised operating conditions an experimental parametric study was performed to achieve better brake thermal efficiency and lower emissions. The optimized operating conditions are listed in the Table 1.

3. RESULTS AND DISCUSSIONS

3.1 Comparison of in-cylinder pressure and heat release rate between CDC and RCCI combustion

Fig. 1 compares the in-cylinder pressure and rate of heat release (RoHR) pattern of CDC and RCCI combustion at 25% of full load condition with respect to engine speed. It is seen that the in-cylinder pressure is higher in RCCI combustion compared to CDC at all tested conditions. This may be due to the burning of more premixed and homogeneous mixture in RCCI combustion as compared to CDC. The compression pressure of RCCI combustion is observed to be lower as compared to CDC due to higher latent heat of premixed methanol fuel which reduces the in-cylinder charge temperature and in-cylinder pressure. The in-cylinder pressure increases with increasing engine speed due increased boost pressure and also more fuel burning inside the cylinder. In Fig.1 it is also observed that two stage heat release rate in CDC due to mixing controlled diffusion combustion. Whereas, in RCCI combustion only premixed combustion phase is observed with higher magnitude compared to CDC due to the presence of more premixed homogenous fuel and higher combustibility character of methanol fuel. Further it is observed that, by increasing engine speed the peak in-cylinder pressure advanced and peak RoHR is delayed.

Fig.2 compares the brake thermal efficiency between CDC and methanol/diesel dual fuel RCCI combustion at different speed and load conditions. Higher brake thermal efficiency is observed in RCCI combustion compared to CDC at all speed and load conditions. Improvement in brake thermal efficiency in case of RCCI is may be due to reduced heat losses and compression work. It is observed that maximum 6% increase in brake thermal efficacy is obtained at 70 Nm torque and 2100 rpm. The increasing engine speed, reduced the brake thermal efficiency due to delayed combustion phasing.

Table 1. Operating Condition

Speed	2100 rpm		2500 rpm		3000 rpm	
Load (Nm)	36	71	35	70	32	63
Energy input (kW)	28	44	34	55	44	62
SOI (° CA bTDC) CDC/RCCI	13/ 13	10/ 10	15/ 15	13/ 13	17/ 17	15/ 15
Inj. Pressure (MPa) CDC/RCCI	40/ 40	70/ 60	50/ 45	75/ 65	55/ 50	80/ 70
EGR (%) CDC/RCCI	0/ 20	0/ 40	0/ 20	0/ 40	0/ 20	0/ 40
MER (%) CDC/RCCI	0/ 50	0/ 70	0/ 48	0/ 71	0/ 50	0/ 70

Fig.2 also shows the comparison of indicated mean effective pressure (IMEP) between CDC and RCCI combustion. The increased IMEP is observed in dual fuel RCCI combustion compared to CDC operation because of higher in-cylinder pressure and reduced compression work. Further it is observed that the coefficient of variation of dual fuel RCCI combustion is slightly higher compared to CDC operation due to variation in the incylinder charge temperature, in-cylinder premixed fuel charge quantity of different operating cycles.

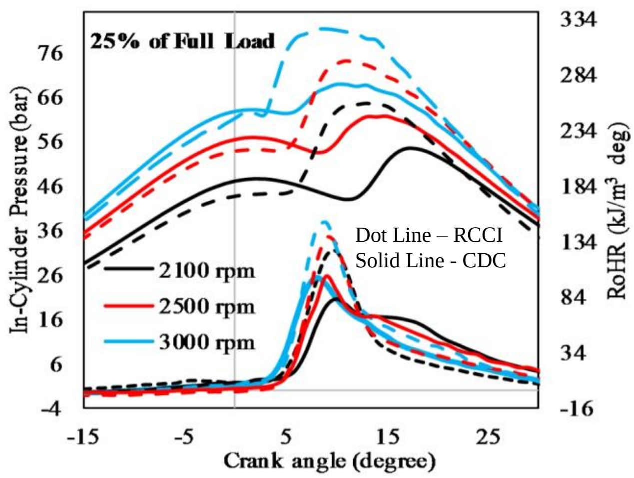

Fig.1 Comparison of in-cylinder pressure and RoHR traces between CDC and RCCI combustion at 25% load conditions

Fig.3 shows the comparison of emission characteristics between CDC and methanol/diesel dual fuel RCCI combustion at various engine speed and load conditions. It is observed that NO emissions are drastically reduced by 80% in RCCI combustion compared to CDC combustion. Further, it is also observed that at all operating regimes NO emission is well below 1.5 g/kWh. The similar results are already obtained by Benejas et al [2] and Pan et al [8] using gasoline/diesel and 2-butanol/diesel RCCI combustion. The RCCI combustion generally operate at lean, homogeneous fuel air mixture which results in reduced local high temperature regions. In addition, the higher enthalpy of vaporization of methanol reduces the in-cylinder temperature and the quick burning features of methanol reduces residence time of high temperature duration. From Fig 3 it is also observed that, increasing engine speed reduces the NO emissions at both CDC and RCCI operation. This may be due to less residence time of high temperature duration in high speed conditions compared to low speed conditions.

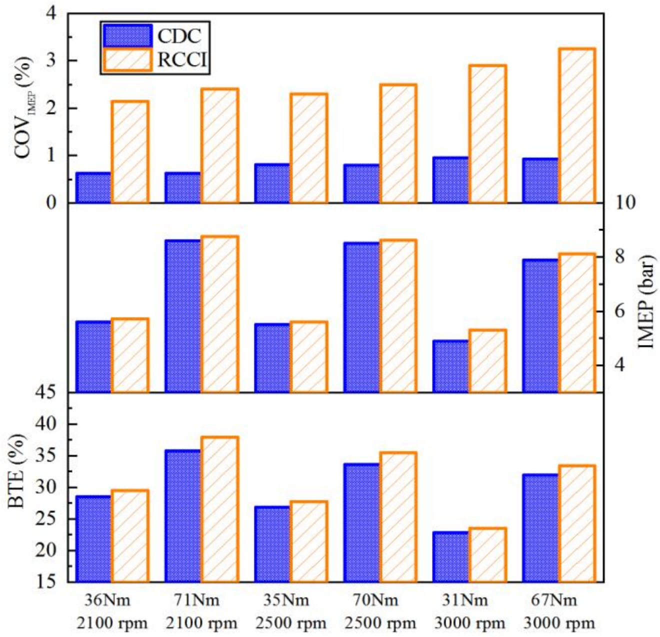

Fig.2 Comparison of BTE, IMEP and COV of IMEP between CDC and Methanol/Diesel RCCI combustion

The exhaust smoke emissions at various speed and load conditions are presented and compared between CDC and RCCI combustion in Fig. 3. The smoke emission increases with an increasing engine speed at both operating conditions because of presence of fuel rich regions due to reduced mixing time with increase in engine speed. The smoke emission was reduced nearly by 85% at RCCI combustion compared to CDC. Methanol/diesel RCCI combustion always operates with lean homogeneous mixture which inhibits the formation of smoke emission. Increase in smoke emission is observed at 50% load compared to 25% load at all speed conditions due to increase in overall fuel air equivalence ratio.

Fig.3 also shows the CO and HC emissions for CDC and RCCI combustion at different speed and load conditions. The increased HC and CO emissions observed in RCCI combustion compared to CDC. The reason may be due to accumulation of early injected fuel in the crevice volume and piston squish area, where the fuel is difficult to be oxidized completely due to lower wall temperature. In addition, lower in-cylinder temperature caused by higher enthalpy of vaporization of methanol leads to reduced oxidation process. The HC emission increases with increasing engine speed at both CDC and RCCI due to reduced mixing period and combustion period. Further, at higher load condition HC emission is reduced due to better in-cylinder charge condition compared to lower load conditions.

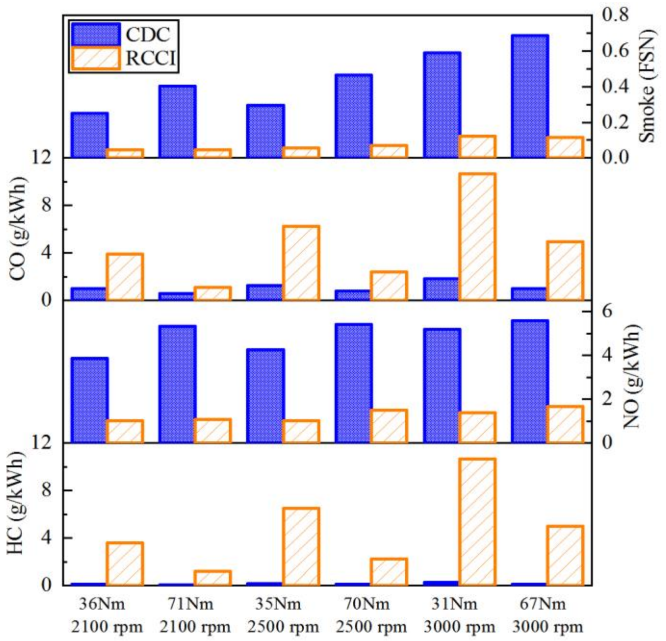

Fig.3 Comparison of various emission between CDC and Methanol/Diesel RCCI combustion

4. CONCLUSIONS

In the present study, reactivity controlled compression ignition combustion mode was demonstrated in a three cylinder turbocharged CRDI diesel engine using methanol as a low reactivity fuel and diesel as a high reactivity fuel. The investigation carried out at different ESC cycle points. Six ESC cycle points including low speed, medium speed and high speed at 25% and 50% load conditions were selected and the RCCI combustion was studied the obtained results are compared with the conventional diesel combustion. The main conclusion are summarized as follows.

1. The maximum in-cylinder pressure and RoHR was higher in RCCI combustion compared to CDC operation at all speed and load conditions.
2. The maximum of 6% increase in brake thermal efficiency is achieved in RCCI combustion compared to CDC operation. Brake thermal efficiency is higher at low speed compared to high speed condition.
3. The combustion of lean, homogenous air fuel mixture reduces the NO and smoke emission simultaneously in RCCI combustion compared to CDC operation.
4. The improvement in indicated mean effective pressure was observed in dual fuel RCCI combustion than CDC. However, slightly higher coefficient of variation is observed in RCCI operation compared to CDC.
5. The hydrocarbon and carbon monoxide emissions are slightly higher in RCCI combustion compared to CDC operation.

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