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Effect of Biodiesel Fuel Injection Timing and Venture for Gaseous Fuel Induction on the Performance, Emissions and Combustion Characteristics of Dual Fuel Engine

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ABSTRACT

Advancing or retarding pilot fuel injection timing in a diesel engine provided with either conventional mechanical fuel injection (CMFIS) or high pressure injection as in common rail fuel injection (CRDI) systems can significantly affect its performance and tail pipe emissions. Performance of diesel engine when fueled with various biofuels as well as gaseous fuels tends to vary with subsequent changes in pilot fuel injection timings. Biodiesel derived from rubber seed oil called Rubber Seed Oil Methyl Ester (RuOME) and hydrogen (H_2) and hydrogen enriched compressed natural gas called (HCNG) both being renewable fuels when used in diesel engines modified to operate in dual fuel mode can provide complete replacement for fossil diesel. In the present study, effect of injection timings and venture design for gas mixing on the performance, combustion and emission characteristics of dual fuel engine fitted with both CMFIS and CRDI injection systems and operated on RuOME and HCNG/hydrogen has been investigated. Results showed that high pressure CRDI assisted injection of RuOME with optimized mixing chamber (carburetor)) for hydrogen induction in dual fuel engine performed improved compared to that with CMFIS. In addition, for the same fuel combinations, CRDI resulted in lower biodiesel consumption, lower carbon monoxide (BSCO) and hydrocarbon (BSHC) emissions and increased NOx emissions than CMFIS operation.

Keywords: hydrogen, hydrogen enriched compressed natural gas, dual fuel engine, conventional mechanical and common rail fuel injection (CMFIS and CRDI)

INTRODUCTION

Worldwide energy demand is increasing as declining fossil fuel reserves and environmental degradation have created global interest in search for renewable and sustainable alternative fuels for power generation and transport sectors. Compression ignition (CI) engines are conveniently operated with wide variety of alternative fuels and these fuels have favorable advantages such as renewability, sustainability, and biodegradability and could address the energy security, environmental and socio-economic issues of a country as well (Banapurmath et al., 2011; Yaliwal et al., 2014; Yaliwal et al., 2016). Several researchers have carried out investigations on diesel engines powered with liquid and gaseous fuels unlike. Accordingly, biodiesels derived from non-edible resources and gaseous fuels such as producer gas, compressed natural gas (CNG) and hydrogen are promising alternative fuel candidates for complete or partial replacement for fossil diesel (Banapurmath et al., 2011; Yaliwal et al., 2014; Yaliwal et al., 2016).

Table 1. Properties of Diesel, and RuOME

Sl. No.	Properties	Diesel	Rubber Seed oil	RuOME
1	Chemical Formula	$C_{13}H_{24}$	----	----
2	Density (kg/m^3)	840	915	880
3	Calorific value (kJ/kg)	43,000	35600	36,010
4	Viscosity at 40^{o}C (cSt*)	2-5	45.65	5.5
5	Flashpoint (^{o}C)	75	215	167
6	Cetane Number	45-55	42	45
7	Carbon Residue (%)	0.1	0.66	----
8	Cloud point	-2	----	7
9	Pour point	-5	----	4
10	Carbon residue	0.13	0.5	0.01
11	Molecular weight	181	---	227
12	Auto ignition temperature (^{o}C)	260		470
13	Ash content % by mass	0.57		0.01
14	Oxidation stability	High	Low	Low
15	Sulphur Content	High	No	No

Biodiesel operation results into comparatively higher smoke, HC and CO and lower NOx emission levels. Therefore, use of biodiesels in engines requires suitable modifications to meet stringent emission norms laid down by Euro/Bharat standards (Tziourtzioumis and Stamatelos, 2012). Transitory performance of engine fueled with CRDI system using blended fuels has been reported. Lower calorific value of biodiesel decreases the engine performance and hence for achieving same power output, more quantity of fuel needs to be supplied per stroke (Senthilkumar et al., 2015). Higher emission levels in biodiesel injected engines can be minimized by the use of gaseous fuel when the same engine is modified to operate in dual fuel engine (Banapurmath et al., 2011; Yaliwal et al., 2014; Sabinus, 2012; Jinlin, 2011). However, because of its high self-ignition temperature and lower cetane number, gaseous fuel operation demands small quantity of pilot liquid fuels to be injected (Banapurmath et al., 2011; Yaliwal et al., 2014; Yaliwal et al., 2016). Diesel engine operation with gaseous fuel in dual fuel mode typically has five stages of combustion phases, instead of the regular four as observed in liquid fueled diesel engines. Diesel engine performance was found to be inferior when fueled with gaseous fuels and the same could be improved by advancing the fuel injection timing, increasing compression ratio, and optimizing both nozzle and combustion chamber combinations (Banapurmath et al., 2011; Yaliwal, et al., 2014; Yaliwal et al., 2016). At higher compression ratio and advanced injection timing, the smoke, hydrocarbon emissions were considerably reduced while NOx emissions increased over the range of operating conditions (Fazal et al., 2011; Agarwal and Assanis, 1998). Use of hydrogen in diesel engine operating in dual fuel mode provides increased power output and lowers the smoke, HC, CO emission levels due to their higher flame speed and lower carbon to hydrogen ratio. In this direction several research attempts have been made to exploit the energy from hydrogen by using different fuel induction/injection techniques such as carburation, continuous manifold injection, timed manifold injection (TMI), direct in-cylinder injection and dual injection systems. Engine knocking was found with hydrogen operation as the quantity of the same was increased beyond certain limit. In addition, problems such as knocking and backfire due to its utilization and the methods to overcome the same has been reported in the literature. Possible methods of hydrogen utilization in diesel engines which are safer than petrol engines have been discussed (Saravanan, 2010; Saravanan and Nagarajan, 2010). But use of hydrogen in dual fuel engine results in to lower engine performance at part load as a result of poor utilization of the gaseous fuel component of the charge. Other problem is associated with spontaneous ignition of hydrogen that leads to knocking within the cylinder at higher power outputs (Miqdam et al., 2014).

From the detailed literature review reported on the utilization of renewable fuels for dual fuel engines, it was found that RuOME as pilot injected fuel using CMFIS and CRDI and HCNG/Hydrogen as inducted fuels for varied pilot fuel injection systems has not been investigated in detail CI engine. In addition, mixing chamber or venture design on the effect of gas and air mixing in dual fuel engines with biodiesel injection has been scantily reported. Hence in this study an attempt has been made to evaluate the performance of the dual fuel engine using such fuel combinations.

The objective of the present experimental work is to study the effect of pilot fuel injection type and injection timing on the performance of dual fuel engine operated on RuOME and HCNG/Hydrogen and comparison of the results of dual fuel operation with the neat base line liquid fuel operation.

FUEL CHARACTERIZATION

In this study, RuOME, a biodiesel derived from the locally available rubber seed oil was used as the injected pilot fuel and HCNG/Hydrogen as the inducted fuel. HCNG/Hydrogen filled cylinder was procured from local

Table 2. Properties of HCNG and hydrogen

Sl. No	Properties	Hydrogen	HCNG
1	Density of Liquid at 15^{o}C, kg/ m^3		---
3	Boiling Point, K		---
4	Lower calorific value, kJ/kg		47170
5	Limits of Flammability in air, vol. %		5 - 35
6	Auto Ignition Temp, K		825
7	Theoretical Max flame Temp, K		2210
8	Flash point ^{0}C		---
9	Octane number		---
10	Burning velocity, cm/sec		110
11	Stoichiometric A/F, kg of air/kg of fuel		----
12	Flame temperature, ^{0}C		1927
13	Equivalence ratio		0.5 - 5.4

Table 3. Specifications of the diesel engine

Sl No	Parameters	Specification
2	Type	TV1 (Kirloskar make)
3	Software used	Engine soft
4	Nozzle opening pressure	200 to 225 bar
5	Governor type	Mechanical centrifugal type
6	No of cylinders	Single cylinder
7	No of strokes	Four stroke
8	Fuel	H. S. Diesel
9	Rated power	5.2 kW (7 HP at 1500 RPM)
10	Cylinder diameter (Bore)	0.0875 m
11	Stroke length	0.11 m
12	Compression ratio	17.5 : 1
Air Measurement Manometer		
13	Made	MX 201
14	Type	U- Type
15	Range	100 – 0 – 100 mm
Eddy current dynamometer		
16	Model	AG – 10
17	Type	Eddy current
18	Maximum	7.5 (kW at 1500 to 3000 RPM)
19	Flow	Water must flow through Dynamometer during the use
20	Dynamometer arm length	0.180 m
21	Fuel measuring unit – Range	0 to 50 ml

industry. The properties of RuOME were measured as per ASTM standards. **Tables 1** and **2** summarize the properties of fuels used in the current investigation.

EXPERIMENTAL SETUP

This section describes the experimental setup used for dual fuel engine operation. Specifications of the CI engine are given in **Table 3**. **Figure 1(a)** and **(b)** shows the experimental setup used for HCNG and Hydrogen induction in dual fuel engine operation. The engine is coupled to an eddy current type dynamometer to regulate the engine braking load. Piezo-electric pressure sensor (range 0-250 bar) measures the in-cylinder pressure. An optical crank angle encoder (Make: Kistler, Model: Type 2613B) determines the crankshaft position to record pressure developed inside the cylinder with respect to crank angle position. In addition, appropriate sensors were used to measure fuel flow rate, temperatures and load. Water flow rate to the engine and calorimeter was measured using suitable rotameters. Manufacturer specified the injection pressure and injection timing (static) as 205 bar and 23°before Top Dead Centre (bTDC) respectively. Injection pressure for liquid fuel were optimized at 240 bar keeping compression ratio constant at 17.5:1 while injection timing was optimized in the study. The engine speed was suitably controlled using governor. The test rig had conventional hemispherical combustion chamber with suitable overhead valves. Continuous supply of water for cooling of calorimeter, engine block and cylinder head was accomplished using separate pumps with suitable rotameters. A nozzle with 5-hole each having an orifice of 0.2 mm size was used to inject biodiesel in the dual fuel engine developed.

Figure 1. (a) Experimental set-up on Dual Fuel Engine with CMFIS and CRDi injection facilities. (b) Photographic view of the experimental test rig

Figure 2. Flash back arrester

HCNG/Hydrogen Supply System

Supply systems were developed for gaseous fuels of HCNG and hydrogen respectively for their induction into the intake manifold of the dual fuel engine developed with pilot injection facility for the RuOME. The gaseous fuels were inducted into the engine cylinder through suitable carburetors developed in-house. Gas flow rates were controlled using suitable pressure regulators ensuring a uniform supply of the gas by constantly monitored its pressure more or less than 2 bars. Hydrogen and HCNG was allowed to flow through a rotameter that were calibrated to supply known flow rate of the metered gases respectively. Flash back arrester, flame arrester and wet type flame trap were connected end to end to prevent fire hazards and induct the metered gas into the intake manifold. Hydrogen flow rate was varied from 0.10 to 0.25 kg/h. Hydrogen is highly inflammable and hence a flashback arrester (acts as a non-return valve) was also used as shown in the **Figure 2.** The wet type flame trap shown in **Figure 3** extinguishes any accidental flame flowing back into the gas supply side and a dry flame arrester used is also shown in **Figure 4**. **Figure 5** shows the venture holder for housing different ventures designed which provides uniform air-gas mixing. **Figure 6** shows the leak detector for hydrogen to ensure safety operation during the experimentation. The engine is operated with pilot injection of RuOME while H_2 and HCNG gases were inducted into the inlet manifold. The flow rate of the liquid fuel was regulated automatically as the engine used was self-governed. The flow rates of gaseous fuels were regulated to suit the given load of engine operation ensuring smooth engine operation without knock.

Figure 3. Wet type flame trap

Figure 4. Flame arrester

Figure 5. Venture holder

Figure 6. Hydrogen leak detector

PERFORMANCE, EMISSON AND COMBUSTION CHARACTERISTICS

Effect of Carburettor Type

Experimental investigation was conducted on dual fuel engine inducting HCNG/Hydrogen into the inlet manifold using three ventures having 12 holes of varied orifice size viz., 3, 6, 9 mm respectively. Pilot injection of RuOME was done using injection systems of CMFIS and CRDI respectively in turn to evaluate the dual fuel engine performance.

Performance characteristics

Effect of venture type on dual fuel engine BTE is presented in Figure 7. Increased BTE for RuOME-Hydrogen was obtained compared to RuOME-HCNG operation due to higher flame velocity and higher energy content of Hydrogen fuel. However, brake thermal efficiency for selected fuel combinations improved with 9 mm size venture compared to others. Homogeneous mixing of air and inducted gas (fuel) with nearly stoichiometric conditions could be responsible for the observed trends. Gaseous fuel being common varied size of the venture orifice is the main influencing parameter on the dual fuel engine performance. HCNG inducted has lower calorific value and lower flame velocity compared to Hydrogen which results into lower energy release rate and hence lower BTE is obtained. Among the ventures used 9 mm size orifice provides proper air-gas mixing and increased equivalence ratio causing complete combustion. BTE with 9 mm venture at 80 % load for RuOME-HCNG and Hydrogen dual fuel operation were found to be 26.65, 27.12% and 28.42% respectively.

Emission characteristics

This section presents emission characteristics of smoke, HC, CO and NO_X of dual fuel engine powered with selected renewable fuel combinations. The emissions were measured under steady state conditions using periodically calibrated devices.

Figure 8 shows venture orifice effect on smoke opacity of RuOME-HCNG and Hydrogen combination. 9 mm venture ensures uniform air and gas mixing resulting in improved combustion and hence lower smoke opacity

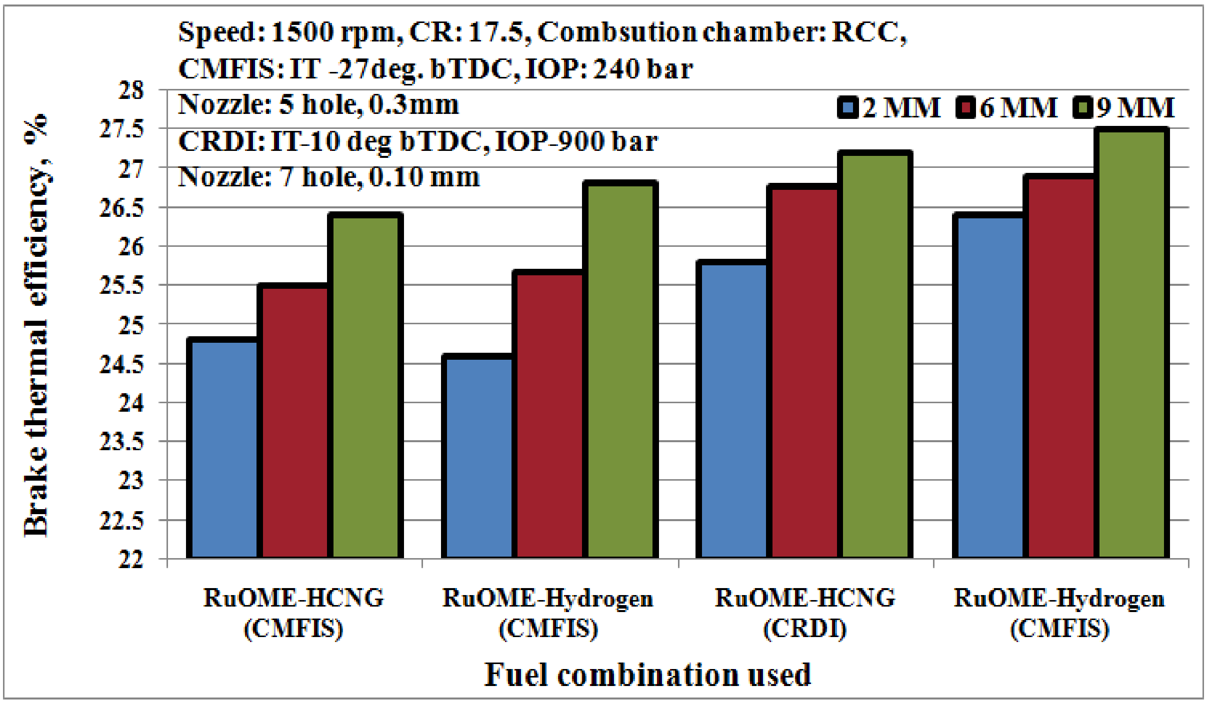

Figure 7. Effect of venture type on BTE

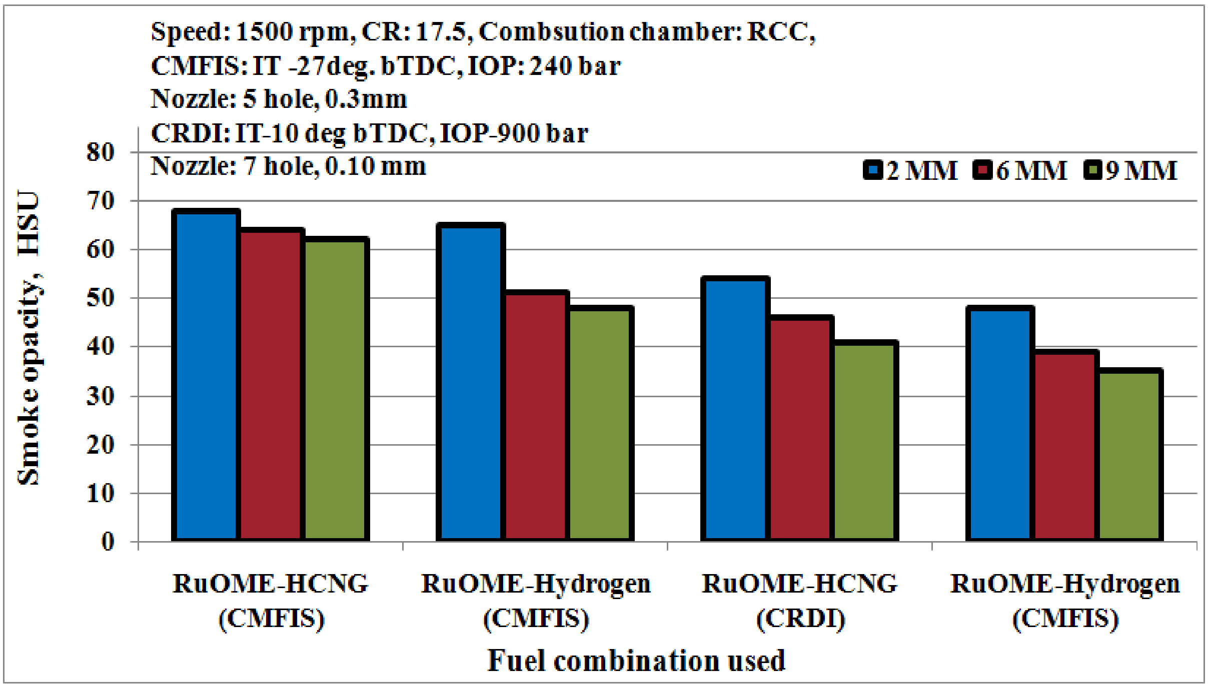

Figure 8. Effect of venture type on smoke opacity

were resulted compared to others. With RuOME injection being common, gaseous fuel properties lead to differences in the smoke levels obtained. Higher smoke levels have been observed with HCNG induction when compared to Hydrogen due to faster burning characteristic helps to burn the pilot injected fuel more efficiently. Smoke levels at 80 % load with RuOME- HCNG/Hydrogen operation and 9 mm venture were 61, 56 HSU and 42 HSU respectively.

HC emissions were lowered for 9 mm venture compared to other as shown in Figure 9. Combustion of viscous biodiesel along with gaseous fuel resulted in to higher HC emissions. 9 mm venturi ensures required air-gas ratio (stoichiometric mixture) compared to other. For 2 and 6 mm ventures, HC emission were higher as improper air-fuel mixing and decreased burning rates were observed. HC for RuOME-HCNG/Hydrogen operations with 9 mm venture were 0.05, 0.042 and 0.04 ppm respectively.

Figure 10 shows the effect of venture size on CO emission for RuOME- HCNG and Hydrogen operation. Larger concentration of CO in the exhaust may be due to partial burning of the pre-mixed air-fuel mixture.

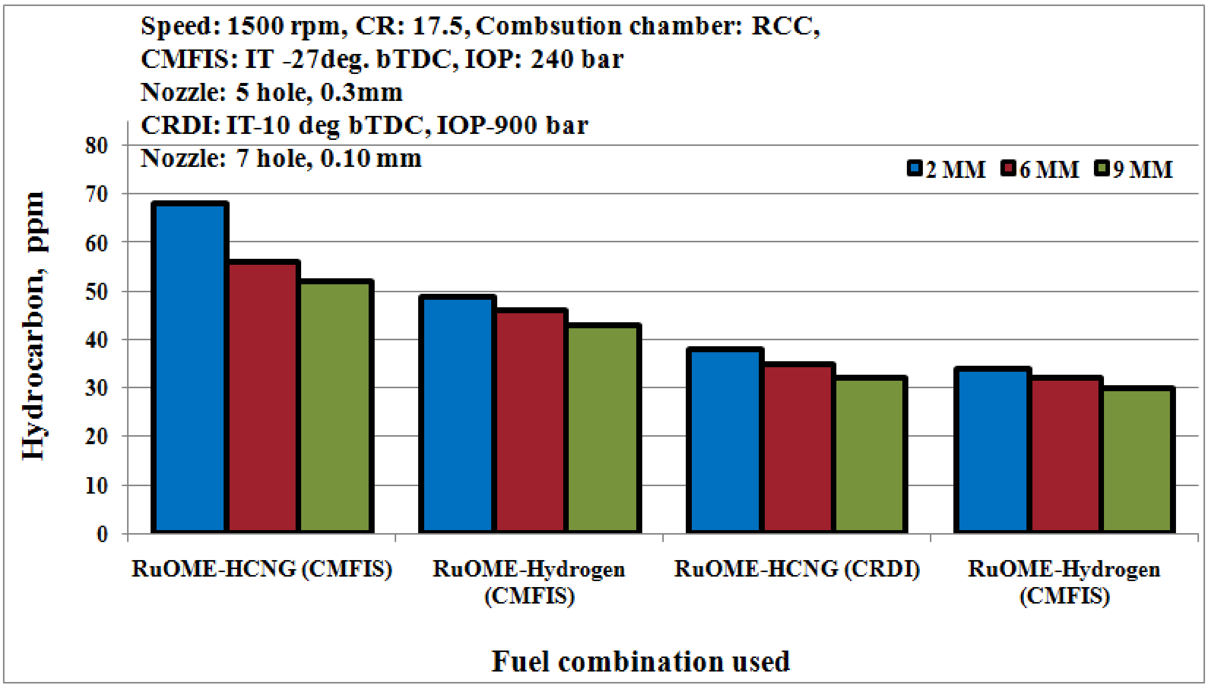

Figure 9. Effect of venturi type on HC

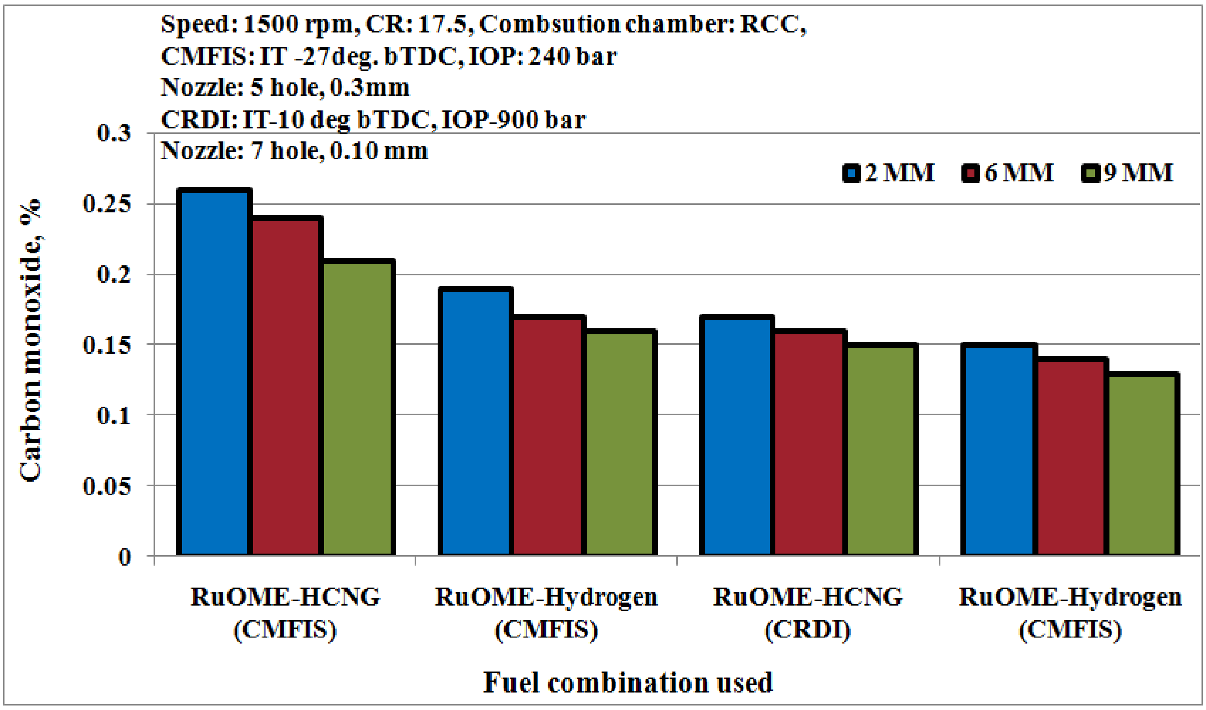

Figure 10. Effect of venture type on CO

Improper utilization of gaseous fuel during combustion of gaseous fuel may lead to higher CO emissions due to combustion inefficiencies. Lower equivalence ratios and quality of fuel-air mixture prevailing inside engine cylinder significantly affects the combustion. However, substitution of gaseous fuel may lessen the quantity of oxygen required for complete combustion hence incomplete burning of gaseous fuel occurs. Increased CO emission levels were noticed due to higher auto ignition temperature of the gaseous fuel. Substitution of air by the gaseous fuel in the inlet manifold could be responsible for this trend. Lower CO emissions resulted with 9 mm venture compared to other for the fuel combinations in dual fuel mode. Comparatively improved air mixing with gaseous fuel may cause slightly improved combustion. CO at 80 % load with RuOME-HCNG and Hydrogen operation using 9 mm venture were found to be 0.5, 0.042 and 0.04% respectively.

For identical fuel combinations, larger NOx levels were found with 9 mm venture compared to other due to enhanced HRR during premixed combustion and reduced HRR during diffusion combustion phase (**Figure 11**). In addition, improved chemical kinetics during delay period further facilitated this trend. At 80 % load, NOx with

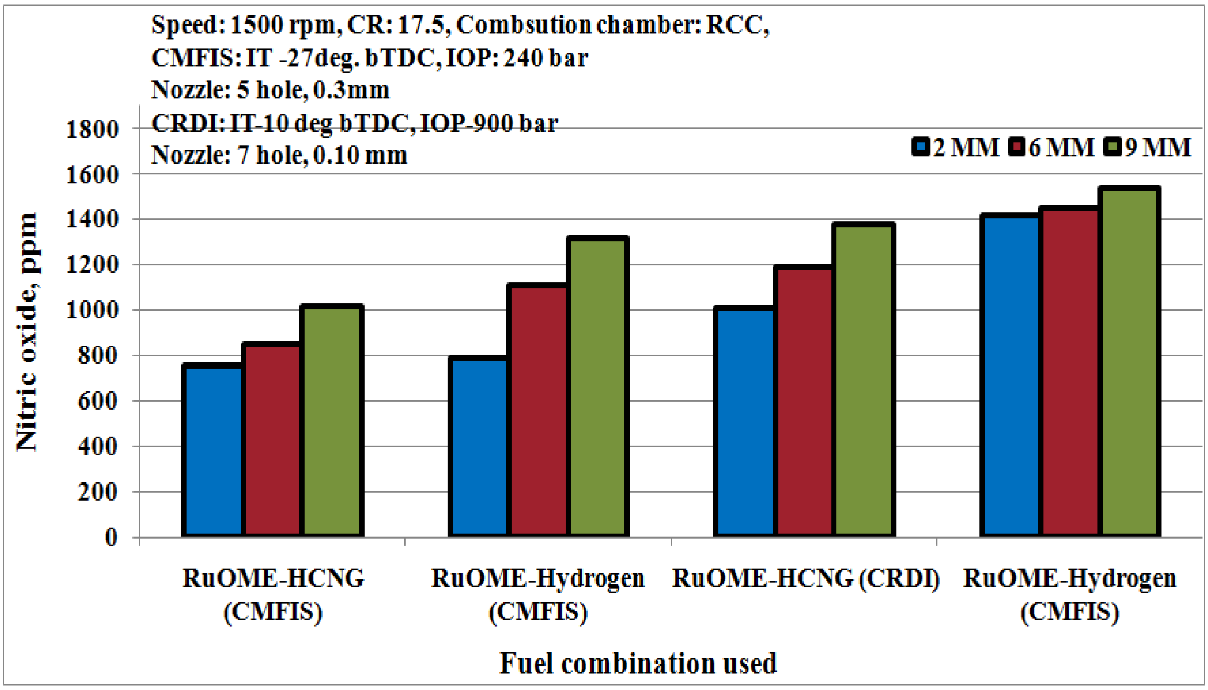

Figure 11. Effect of venturi type on NO_X

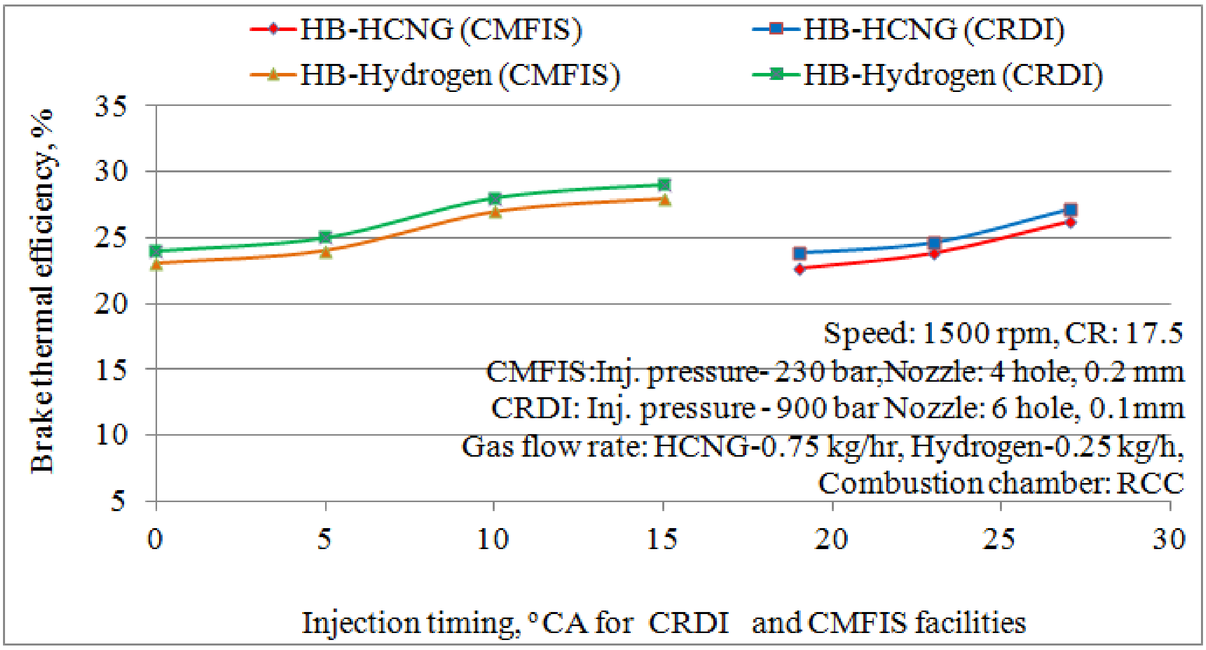

Figure 12. Effect of fuel supply system on BTE

HB-Hydrogen operation using 2, 6, 9 mm gas entry ventures were 68, 74 and 78 ppm respectively. Higher HRR during premixed combustion for with HB-Hydrogen combination using 9 mm venturi gave enhanced BTE with increased NO_X levels.

Effect of injection timing

In this section effect of varied pilot fuel injection timing of RuOME on the performance of dual fuel engine inducted with gaseous fuels of HCNG, and Hydrogen respectively is discussed. During the engine operation, engine speed was maintained constant at 1500 rpm with a pilot fuel (RuOME) injection pressure maintained at 240 bar and compression ratio of 17.5. The flow rates for HCNG and Hydrogen were maintained at 0.75 and 0.25 kg/h respectively.

Performance characteristics

Effect of pilot fuel injection timing on brake thermal efficiency for dual fuel engine with CMFIS and CRDI injection facilities at 80% load is presented in Figure 12. For both CMFIS and CRDI and for all the fuel

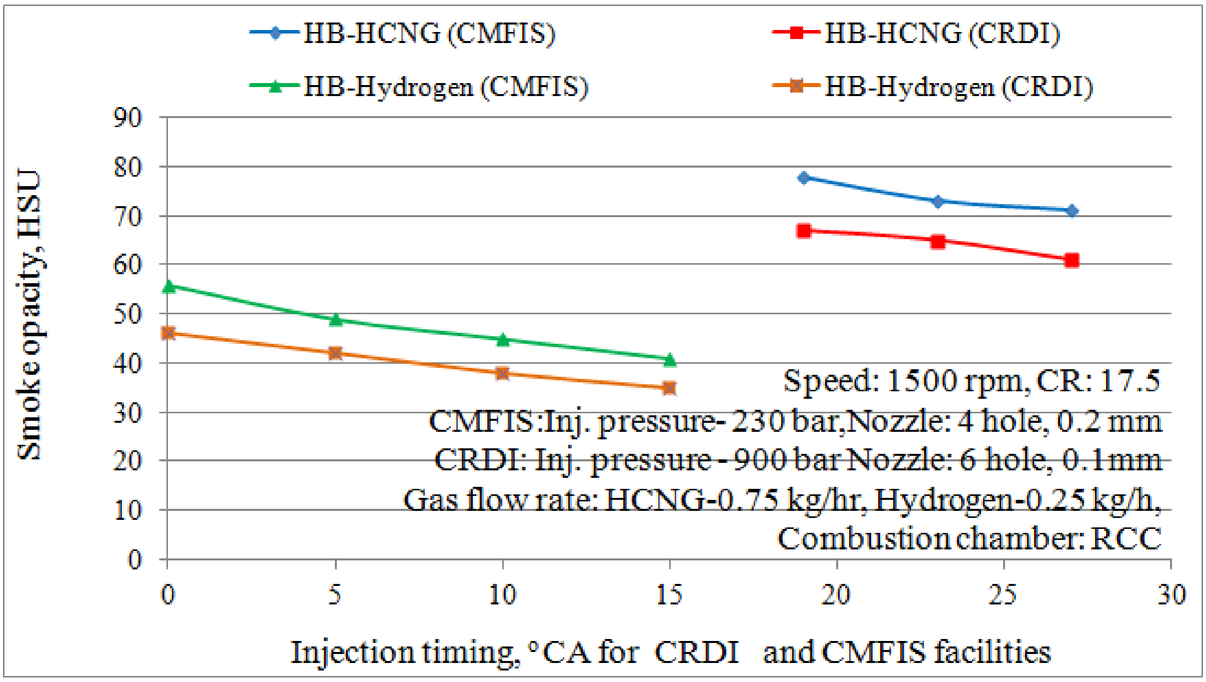

Figure 13. Effect of fuel supply system on smoke opacity

combinations, BTE increased as the pilot fuel injection timing was advanced as this would provide more time for inducted gaseous fuel burning. Further enhanced engine performance and smooth operation was noticed for advanced pilot fuel injection. Advancing the fuel injection timing lead to longer ignition delay resulting in increased chemical kinetics and fuel mixing rates. Enhanced BTE with slight increased specific fuel consumption was observed for the advanced injection timings. Increased cylinder pressure and peak pressure rise rate leads to enhanced BTE and this becomes more pronounced with CRDI operation compared to CMFIS facility. In CRDI RuOME is injected at higher injection pressure nearly 3.75 times more than that in CMFIS facilitates improved mixing of fuel, air and gaseous fuel combinations. The brake thermal efficiency for RuOME- Hydrogen fueled dual fuel engine with CRDI arrangement at optimized injection timing of pilot fuel at 10^{o}BTDC were found to 26.4% and 27.5, respectively at 80% load. RuOME fuel being common increased flame velocity and higher calorific value of the Hydrogen inducted results into improved combustion.

Emission characteristics

Smoke opacity emissions

Smoke opacity variation of dual fuel engine fueled with selected fuel combinations for varied injection timing of pilot fuel (RuOME) at fixed brake power is shown in Figure 13. For both versions of CMFIS and CRDI facilitated dual fuel engine lower smoke levels were resulted for advanced injection timing as improved combustion of the injected pilot fuel along with gaseous fuel induction occurs. Smoke emission reduction with advanced pilot fuel injection timing could be due to the fact that, inducted gaseous fuel consists of lower C/H ratio and replaces part of biodiesel injected in the cylinder. In CRDI mode as RuOME is injected at higher injection pressure improved mixing of fuel, air and gaseous fuel combinations occurs reducing the smoke emissions drastically. Further it may be noted that liquid injected fuel being same, properties of inducted gaseous fuel has an effect on smoke emission pattern. Accordingly, with hydrogen induction due to its rapid flame travel through the combustion chamber leads to complete burning of liquid fuel injected and hence its addition inhibits the soot emission levels. During the dehydrogenation of the liquid fuel, the overall H/C ratio, inhibits the soot nucleation, and OH radicals made available through the hydrogen–oxygen reaction mechanism observed with RuOME-Hydrogen operation. Further, it is observed that decreased smoke levels were resulted for CRDI operation compared to CMFIS facility due to better utilization of available air for mixing with high pressure injection of the liquid fuel droplets.

HC and CO emissions

HC and CO variation of dual fuel engine fuelled with selected fuel combinations for varied injection timing of pilot fuel (RuOME) at fixed brake power is shown in Figures 14 and 15. For both versions of CMFIS and CRDI facilitated dual fuel engine lower HC and CO levels were resulted for advanced injection timing as improved combustion of the injected pilot fuel along with gaseous fuel induction occurs. Advanced injection timing improves combustion, with increased BTE as more heat is released during premixed combustion. Comparatively higher injection pressures (nearly 3.75 times) with CRDi arrangement ensures uniform mixing of fuel combinations and

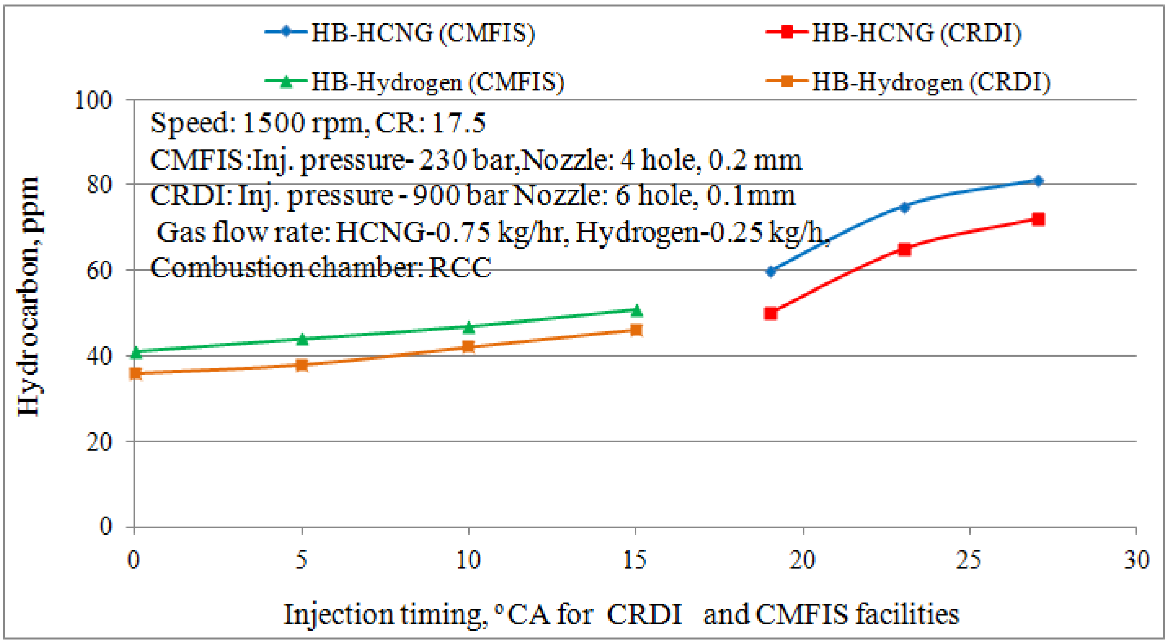

Figure 14. Effect of fuel supply system on HC

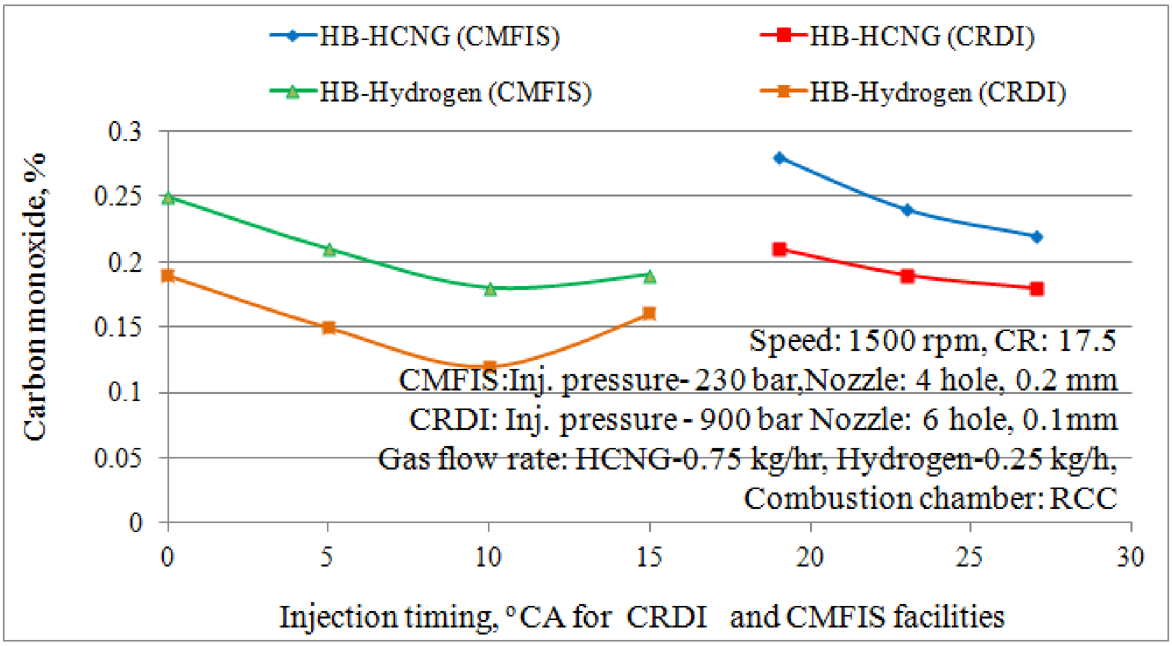

Figure 15. Effect of fuel supply system on CO

hence reduced HC and CO emissions result when compared to its counterpart CMFIS. Further, it is observed that use of injection system significantly affects the emission levels. In this context, for the same pilot fuel injection, decreased HC and CO levels are obtained for CRDI operation compared to CMFIS facility due to better combustion caused by the optimum utilization of available oxygen for mixing of gaseous fuel with liquid fuel droplets. For the same pilot injected fuel, the reduction of HC and CO levels with Hydrogen induction was more effective compared to HCNG dual fuel operation. Longer ignition delay and better spray penetration prior to ignition with increased pilot fuel injection timing may be responsible for the trends presented. CO emission levels are mainly due to partial burning of fuel. Air-fuel ratio relative to stoichiometric conditions is the major factor affecting CO levels in the exhaust. CO levels decreased drastically for the dual fuel operation with both Hydrogen induction and CRDI facility which results into leaner equivalence ratio and better mixing with air. This enhances the combustion efficiency compared to the operation with HCNG fuel. Higher HC and CO levels were noticed with CMFIS facility and when HCNG was inducted in dual fuel engine. It may be due to preparation of lean mixture during the ignition delay and under mixing with pilot fuel leaving the injector nozzle at lower velocity. This effect is more pronounced in HCNG inducted operation.

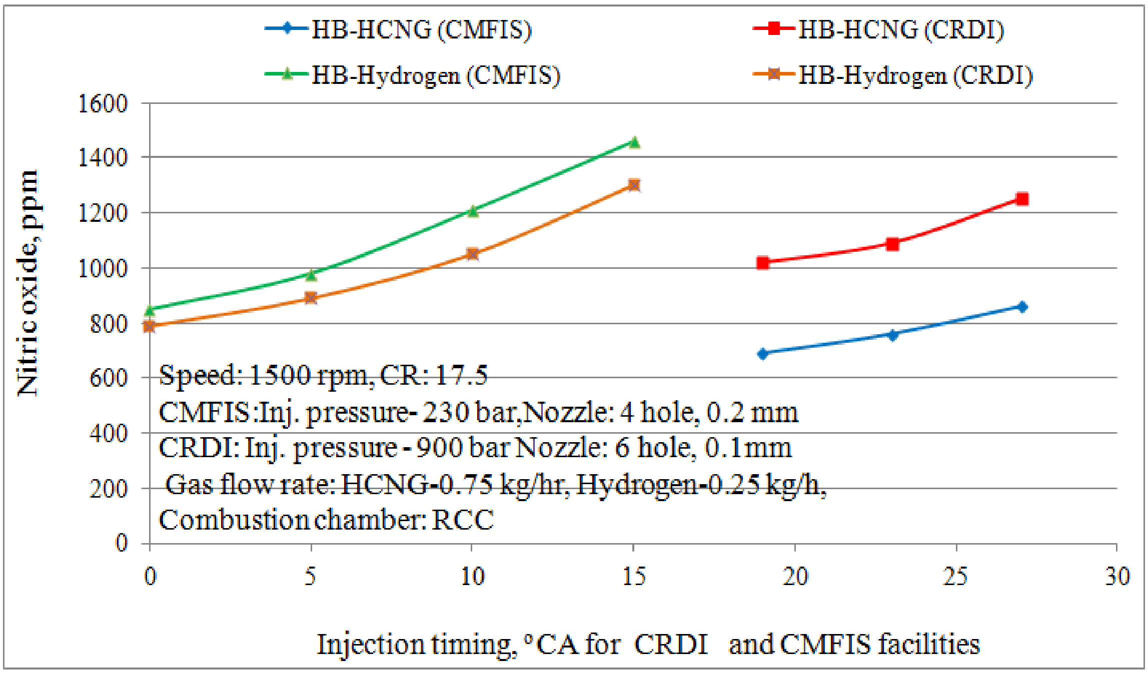

Figure 16. Effect of fuel supply system on NOx

NOx emission

Figure 16 shows the variation of NO_X in dual fuel engine fuelled with selected fuel combinations for varied injection timing of pilot fuel (RuOME) at fixed brake power. NO_X increased with advanced injection timing of pilot fuel in both versions of CMFIS and CRDi injections as it facilitated increased chemical kinetics and decreased heat release rate during diffusion combustion. Adiabatic flame temperature changes may further influence the higher NO_X formation when pilot fuel injection timing gets advanced. For the same pilot fuel injection, increased NOx levels were obtained for CRDI when compared to CMFIS facility due to increased premixed combustion caused by the optimum utilization of available oxygen and increased combustion temperature. For all the fuel combinations used, NOx emissions were higher for injection timing of 10^0 bTDC with CRDI and 27^obTDC bTDC with CMFIS in comparison to other injection timings. RuOME-Hydrogen combination showed higher NOx levels compared to RuOME-HCNG combinations due to increased flame propagation and higher energy content of the hydrogen.

Combustion characteristics

Ignition delay (ID) and combustion duration (CD)

Figures 17 and **18** show the variations of ID and combustion duration CD with injection timing for dual fuel engine using both CRDI and CMFIS system respectively. Higher premixed combustion caused by the higher gas temperature with use of CRDI system showed decreased ID and CD. However, CMFIS injection system operating with lower injection pressures provide larger fuel droplets with increased ID and CD. HCNG with CRDi leads to increased ID and CD caused by the lower flame speed with retarded combustion phasing in contrast to the hydrogen induction. However, gaseous and pilot injected fuels requires more time to mix leading to decreased chemical kinetics. Hence, ID and CD both will be increased for HCNG operation.

In-cylinder pressure variation with crank angle

Figure 19 shows in-cylinder pressure variation with crank angle for dual fuel engine using both CRDI and CMFIS system respectively at varied injection timing and at 80% load of engine operation. For fixed load of engine operation nearly 100 cycles of pressure versus crank angle data were recorded and averaged pressure versus crank angle are presented for the analysis of the results thus obtained and the Heat release rates (HRR) were calculated using 1-D thermodynamic equation. Higher in-cylinder pressures resulted for dual fuel operation with advanced injection timing at 10^obtdc for CRDi compared to 27^obtdc for CMFIS injection facility. Rapid combustion of the fuels occurs with CRDi and hence higher peak pressures are obtained along with higher combustion temperatures prevailing inside the engine cylinder at increased injection pressures. However, for the same pilot fuel injection of RuOME in dual fuel engine with hydrogen induction resulted in higher cylinder pressures due to increased mixing rates leading to complete combustion when compared HCNG induction.

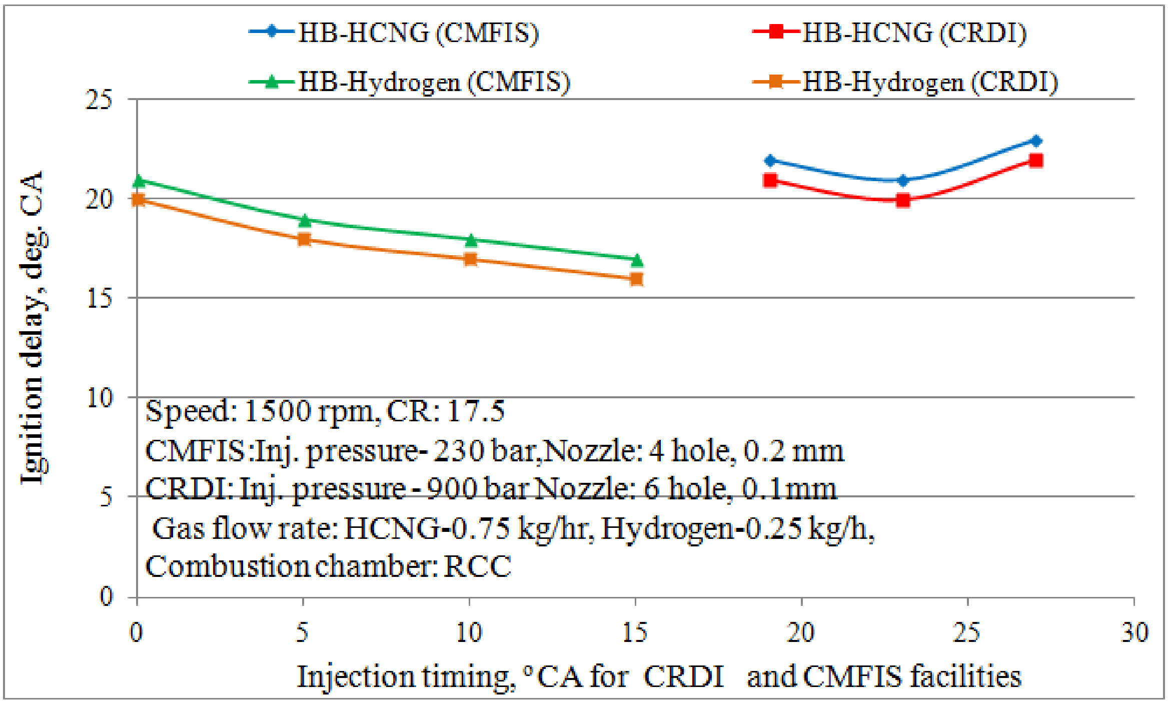

Figure 17. Effect of injection timing on ignition delay

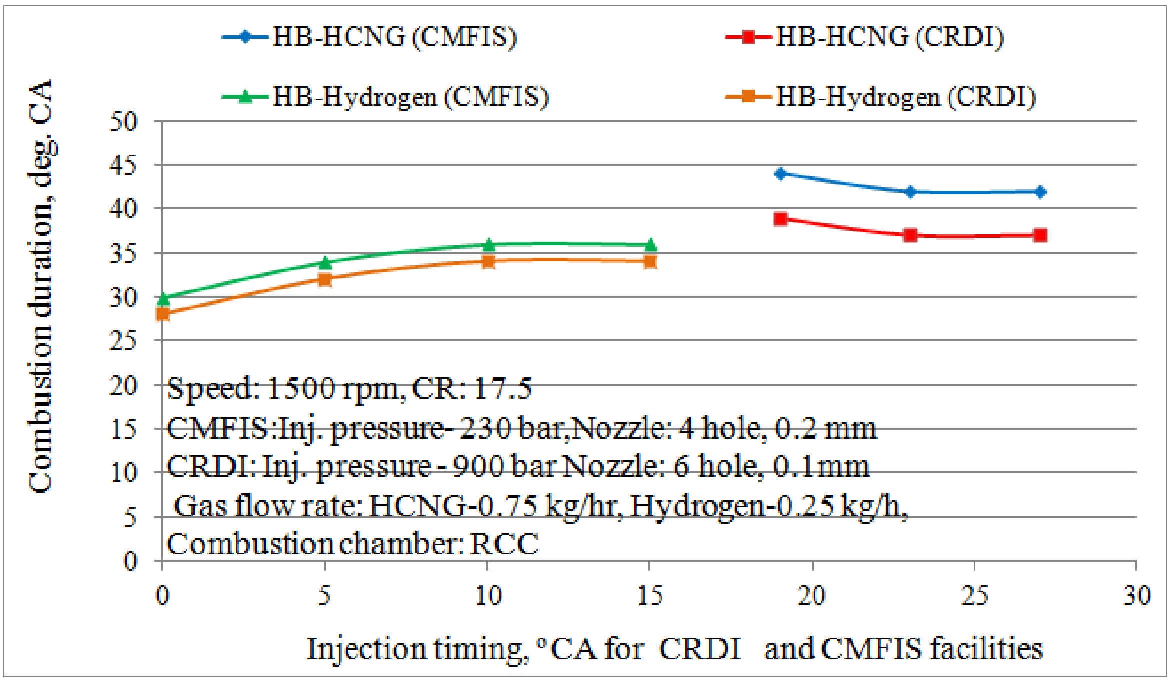

Figure 18. Effect of injection timing on combustion duration

Figure 20 shows Heat release rate (HRR) variation with crank angle for dual fuel engine using both CRDI and CMFIS system respectively at varied injection timing and at 80% load of engine operation. Higher HRR resulted for dual fuel operation with advanced injection timing at 10^{o}btdc for CRDi compared to 27^{o}btdc for CMFIS injection facility. Rapid combustion of the fuels occurs with CRDi and hence higher premixed combustion were obtained. However, for the same pilot fuel injection of RuOME in dual fuel engine with hydrogen induction resulted in higher HRR rates due to increased mixing rates leading to complete combustion. In CRDi facility HRR increased with Hydrogen, due to its higher energy content, better air-fuel mixing rates, larger flame speed and advanced or increased combustion phasing. Higher premixed combustion was noticed with RuOME-Hydrogen combination and CRDI system when compared to HCNG induction.

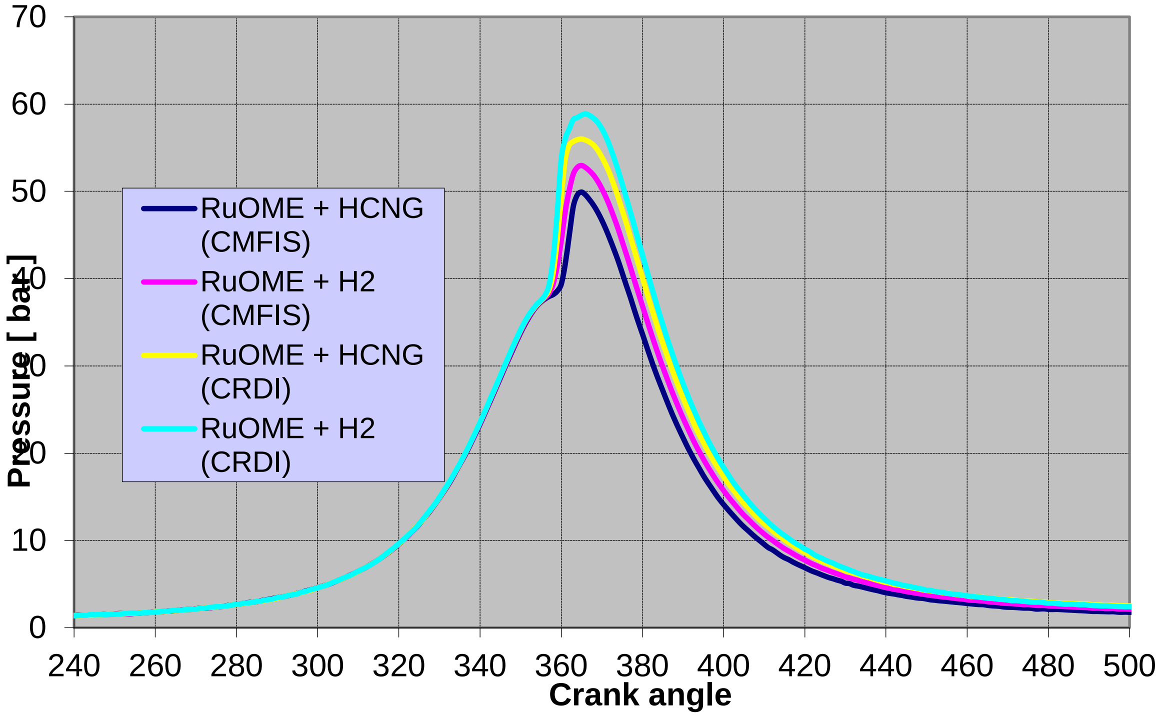

Figure 19. Effect of fuel injection timing on cylinder pressure at 80% load

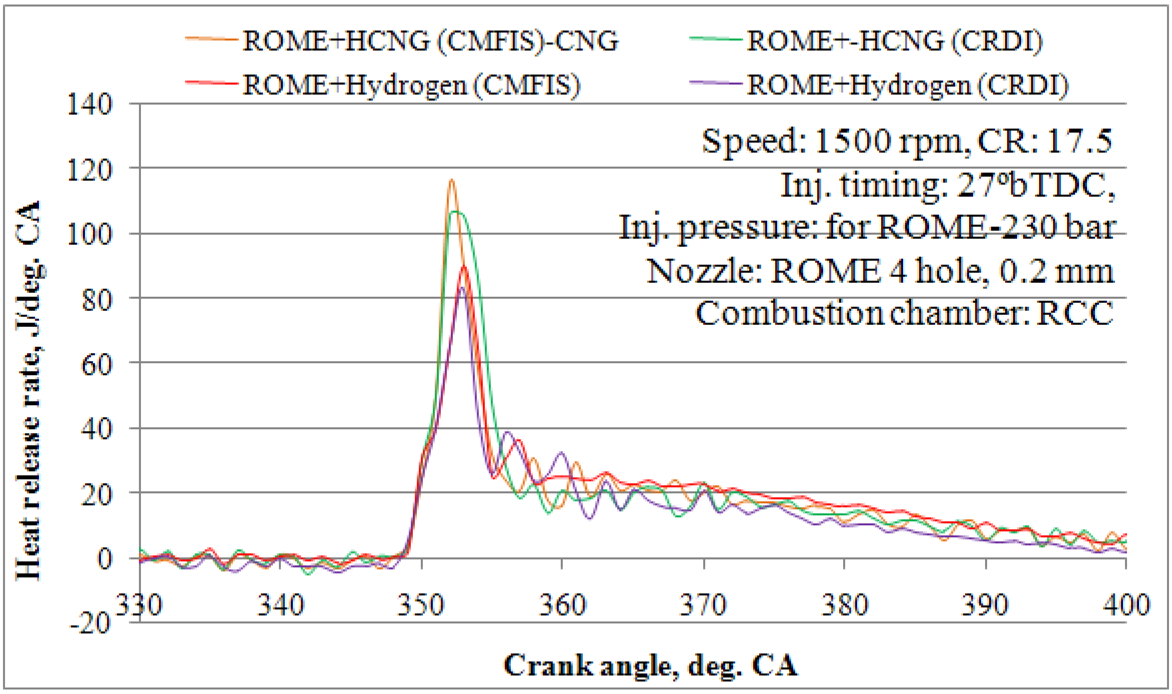

Figure 20. Effect of injection timing on HRR at 80% load

CONCLUSIONS

From the exhaustive research work undertaken on the feasibility of renewable fuels such as HCNG, Hydrogen and RuOME and their usage for diesel engine applications the following conclusions were drawn.

- The developed hardware for the CRDi and CMFIS facilitated dual fuel engines worked satisfactorily.
- Injection of RuOME biodiesel at higher injection pressures using CRDI when compared to CMFIS in dual fuel engines operated on gaseous fuels of hydrogen and HCNG improves the performance significantly. However increased NOx emissions with such high pressure injection systems can be suitably addressed using exhaust gas recirculation methods.

- Advancing the injection timings in both CMFIS and CRDi facilitated dual fuel engines with selected fuel combinations of the RuOME and HCNG/hydrogen improved the engine performance significantly. However, NOx emissions increased drastically.
- Type of gaseous fuel inducted like HCNG and hydrogen will affect the performance of the dual fuel engine significantly as RuOME alone was injected as a pilot fuel for combusting the compressed air and gaseous fuel mixtures respectively.

CRDi assisted dual fuel engine fueled with RuOME-HCNG and Hydrogen combinations at optimized injection timing of 10°bTDC and injection pressure of 900 bar resulted in improved engine performance as compared to the dual fuel operation with CMFIS at optimized conditions of 27°BTDC and 240 bar respectively. Higher brake thermal efficiency, reduced smoke, hydrocarbon and carbon monoxide and higher NOx emissions were obtained when compared to HCNG operation. However, NOx emissions were found to be higher.

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