Experimental Study of the Effect of Compression Ratio on the Characteristics of a Biogas Fueled Dual Fuel Compression Ignition Engine

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Abstract- The influence of compression ratio on the characteristics of combustion, emission and performance in a dual fuelled compression ignition (CI) engine using biogas with diesel as the pilot fuel have been explored. An attempt to study the application of biogas produced in a floating drum type bio digester using food wastes feed from the Boys' Hostel mess of National Institute of Technology Manipur, India; in the engine has been made. This investigation aims at revealing the impact of compression ratio (CR) on the characteristics of combustion, emissions and performance of a CI engine. The experiments were executed at four different CRs, viz. 16.5, 17, 17.5 and 18 under four distinct load settings of engine, viz. 25%, 50%, 75% and 100% respectively. The diesel only approach shows better performance and emission as compared to dual fuel approach except for nitrogen oxides (NO_x) emissions for all the load settings. The results from the investigation manifested an overall superior characteristics of combustion, emissions and performance at CR = 18 as compared to the other values in the dual fuel approach and also improvement of performance and emission is observed with increase in CR. The maximum brake thermal efficiencies (BTEs) for the dual fuel approach observed at full load for CRs 18, 17.5, 17 and 16.5 were found to be 20.1%, 18.2%, 16.4% and 16.2% respectively.

Keywords Biogas; CI engine; kitchen waste; performance; dual fuel; combustion; emission.

1. Introduction

Power is a vital requisite for diverse sectors like irrigation, agriculture, locomotives, marine, military defence, transportation, production of electricity and telecommunication. Compression ignition (CI) engines are the foremost source of generation of power, predominantly for use in transportation and agriculture. Power production in CI engines is accomplished primarily through the combustion of diesel, a rapidly depleting fossil fuel. The human population explosion has led to the speedy drain of global fossil fuel reserves. Additionally, combustion of fossil fuel has adverse impact on the ecology in the form of acid rains, global warming, etc.

The noxious pollutants comprising of nitrogen oxides (NO_x) and particulate matter (PM) are discharged into the atmosphere by CI engines. Human subjection to these pollutants has been identified to pose numerous health vulnerabilities. Exhausts of diesel engines have been categorized as probable human carcinogen [1]. Major prominence has been targeted towards switching over to renewable energy sources to minimize the above complications. In 2017, renewable energy has been accounted for 10.3% and 3.1% of total global energy consumption for heat and transport correspondingly [2]. Several investigations have been reported on the swap of fossil fuel with biofuel in the CI engines.

Unlike the fossil fuel, biofuels are produced through biological processes. Biofuels comprise of liquid fuels like biodiesel, bioethanol and gaseous fuels like biogas. Biodiesel is produced through transesterification of animal based fats or vegetable oils. Biodiesel has inherent high cetane number, lubricity and nearly no sulfur content [3]. Biogas is another promising gaseous biofuel produced through the fermentation of organic matter, such as food scraps, sewage and animal manure, in the absence of oxygen. It comprises chiefly of methane (CH_4) and carbon dioxide (CO_2) and trace measures of hydrogen sulfide (H_2S), in addition to sulphide compounds, volatile organic compounds, siloxanes, aromatics, and halogens. Many studies had been conducted for the production of biogas from different biomass sources. O. J. Reátegui et al. [4] considered using cattle manure enriched with waste from slaughterhouse as a potential substrate for the production of biogas while Y. Ulusoy and A. H. Ulukardesler [5] also studied olive-mill wastes as an alternative. H. N. Singh et al. [6] experimentally investigated the production of biogas using starch-rich food waste at different water-substrate ratio and temperature. In [7], I. Syaichurrozi et al. also investigated the biogas fermentation co-digestion vinasse waste and tofu-processing wastewater within a wide range. Anaerobic co-digestion of cafeteria, vegetable and fruit wastes for biogas production was further explored by M. R. Al Mamun et al. [8]. Biogas besides, being eco-friendly, efficient solution to waste management problem, may lead to corrosion of metal parts owing to the presence of H_2S, lesser calorific value and flame speed owing to the presence of CO_2 [9]. Biogas finds its use in spark ignition (SI) engines attributing to its high octane number and high temperature of self-ignition and thereby being knocking resistant. Even though SI engines powered with biogas exhibit greater CR in contrast to those of petrol, the presence of CO_2 and N_2 as diluents lower the flame speed, flammability limit, power output, calorific value and influence the in-cylinder characteristics of combustion [10]. Quite a portion of investigational experiments have reported on the characteristics of emissions, performance and combustion of the SI engines powered with biogas [11]–[15].

Various studies have been reported on the complementation of diesel with biogas in slightly modified CI engines, with the self-ignition temperature of biogas being high. The methodology comprise of preliminary supply of a combustible blend of biogas and fresh air in the cylinder which is later ignited with the injection of slight amount of diesel/ biodiesel. CI engine performance stability is enhanced by the faster and complete combustion due to the multi-point ignition sources generated by diesel injection, despite the higher maintenance cost and the threat of repeated failures of injector. Mustafi et al. [16] examined the single and dual fuel combustion approaches of CI engine powered with natural gas and biogas, resulting in longer ignition delays but lesser combustion periods, lesser emissions of NO_x and PM and greater maximum net heat release in dual fuel approach in contrast to diesel only approach. Luijten and Kerkhof reported a characterization of the volume and thermal efficiencies against air-excess ratio and output power for a pure jatropha oil and diesel powered diesel motor generator [17]. Barik and Murugan conducted an experimentation of a DI engine powered with diesel and biogas obtained from de-oiled cakes, which resulted in greater cylinder peak pressure, lengthier ignition delay and lesser emissions of NO and smoke for the dual fuel approach in contrast to the diesel only approach [18]. In another investigation, [19] they engaged a diethyl ether (DEE) port injection strategy to boost the efficiency, improve the fuel consumption and ignition delay of a biogas-Karanja methyl ester (KME) dual fuelled engine as that of a diesel approach. Yoon and Lee [20] investigated a diesel engine dual powered with biogas and biodiesel which brought about lower peak pressure, heat release and superior reductions in emissions of soot for the biogas-biodiesel approach at low load in contrast to biogas-diesel approach. Emissions of NO_x were lesser for dual fuel approaches than the single fuel approach. In an investigation by Ambarita H. [21] of a diesel-biogas powered dual fuel CI engine, the concentration of methane and the flow rate of biogas intensely influenced the brake thermal efficiency. Also, the dual fuel approach resulted in greater specific fuel consumption and output power than the diesel only approach. Many researches were conducted to examine the influence of the incidence of CO_2 in biogas [22], [23]. The engine performances were affected by the negative effect of CO_2 with a reduction in the flame speed and heat capacity of biogas. To disclose the effects of CR on the performance, emission and combustion of dual fuel engine powered by biogas, Bora et al. [24] investigated on different CRs which resulted in rise brake thermal efficiencies, reduction in emissions of carbon monoxide (CO) and hydrocarbon (HC) with an increase in CR for dual fuel approach. The enhancement of emission characteristics and efficiency of many dual fuel engines powered with biogas were experimented through the optimization of IT of the pilot fuel [25]–[27]. Further, experimental study of biogas power dual fuel engine coupled with exergy analysis were conducted to improve the emissions and performance characteristics, along with hydrogen supplementations [28] and advanced injection timings [29]. C. Díaz et al. also conducted numerical investigation of the laminar flame speed and flame structure of biogas/H2 fuel mixtures from pure biogas to biogas with an addition of hydrogen [30]. In a similar work [31], experimental and theoretical study was made by V. K.Yadav et al. that signified the improvement in combustion characteristics with addition of even a small amount of hydrogen. Additionally M. Maizonnasse et al. [32] gauged phase separation in concurrence with pre-heated raw biogas as a substitution of biogas free of sulphur compounds as the untreated raw biogas leads to sulphidation and corrosion of engine components. W. Anggono [33] explored the flammability limits and laminar burning velocities at various pressure of biogas containing nitrogen.

The basic intention of this experimentation is to study the application of biogas produced through the anaerobic digestion of food wastes generated at the Boys' Hostel mess of NIT Manipur, India; in a dual fuel CI engine with the pilot fuel, diesel. This endeavour would help in converting the kitchen wastes generated in the institute to power as a sustainable source of energy and solving the problem of waste disposal. This investigation aims at revealing the impact of CR on the characteristics of combustion, emissions and performance of a CI engine.

2. Materials, Methodology and Experimentation

2.1. Test fuel

Biogas, obtained by the anaerobic digestion of kitchen wastes was used as primary fuel with diesel as a pilot fuel for the experimentation. Biogas was produced using kitchen waste, collected from NIT Manipur Boys' Hostel, Langol, Manipur, India in a floating drum type bio-digester. Fig 1 shows the typical kitchen waste feedstock configurations. The concentration of methane (CH_4) in biogas produced was observed to vary from 57-60% by volume. However, this variation can be neglected as this does not have notable influence on the combustion [34]. Properties of biogas and diesel fuel are listed in Table 1.

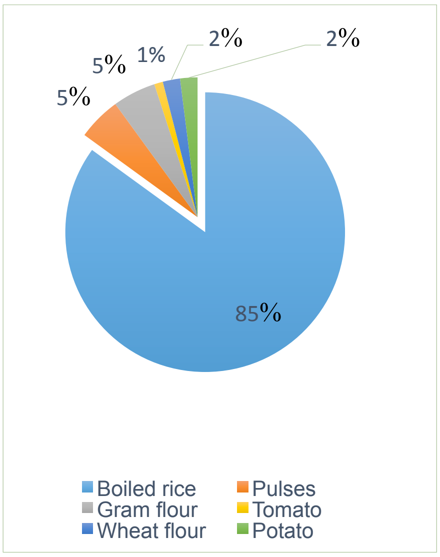

Fig 1. Typical kitchen waste configuration collected from NIT Manipur Boys' Hostel Mess.

2.2. Engine setup

The experimental works of the present study were carried out in the advanced IC engine laboratory, NIT Manipur, India. A 3.7 kW single cylinder, variable compression ratio (VCR), four stroke, multi-fuel engine was employed to run in biogas-diesel dual fuel approach. The detailed specifications of test engine are listed in An eddy current dynamometer (make: PowerMag) was adopted to apply load on the crankshaft of engine. For recording temperature, a number of thermocouples of K type were attached at several points in the engine setup as shown in Fig. 2. Optical sensors fitted in burette were used for measuring liquid fuel consumption. A non-contact type PNP sensor was used to gauge the speed of engine. The frequency of the pulse output for each crankshaft revolution produced by the sensor was transformed into voltage output and sent to a computer via a data acquisition system. Acrylic body rotameters present in the test setup were used for recording flow rate of water to the engine and calorimeter. A calorimeter fitted with several K type thermocouples, was used for heat balance analysis. A piezoelectric sensor (make: Kistler-6613CA) mounted on the cylinder head and connected to a charge amplifier gauged the combustion pressure. For exhaust gas measurement, Testo 350 portable gas analyzer was used. Links were established between all the sensors and a data acquisition device that was linked to a computer via USB port. Windows based software (Engine Test Express) was used to measure and record the results.

Table 1. Properties of biogas and diesel [27], [35].

Properties	Biogas	Diesel
Chemical composition	CH4– 57%, CO2 – 41%, CO – 0.18%, H2 – 0.18% H2S + Moisture – Balance	C12H26
Auto-ignition temperature (℃)	650	553
Density (kg/m3)	1.2	830
Cetane number	-	50
Stoichiometric air fuel ratio	10	14.92
Lower calorific value (MJ/kg)	17	43.8

Table 2.

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air fuel ratio		
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Table 2. Specifications of test engine.

Sl. No.	Parameters	Specifications
1	Engine type	Single cylinder, variable compression ratio, multi-fuel, four stroke engine
2	Compression ratio	9.3:1-18:1
3	Bore & stroke	80 x 110 mm
4	Swept volume	553 cm^3
5	Dynamometer	Eddy current
6	Rated speed	1500 rpm
7	Rated brake power	3.7 kW
8	Fuel injection timing	23.0 °CA before TDC
9	Nozzle injection pressure	200 bar

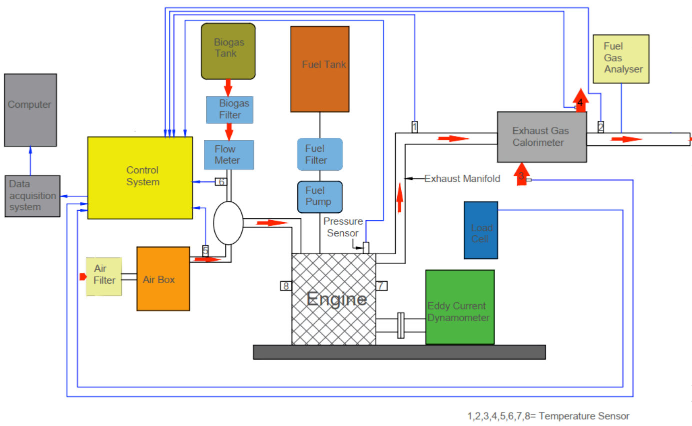

Fig. 2. The test engine setup layout.

Dual fuel operation of CI engine with biogas and diesel required a minor modification in the intake manifold. This modification involved installation of a gas mixture of venturi type in the intake manifold for mixing the biogas and air. The measure of flow rate of biogas is achieved through a gas flow meter. Variation of CR of the test engine setup was achieved via changing the volume of the head gasket which is dependent on the compressed thickness of the gasket. Adding a thicker gasket increased the head volume and reduced the compression ratio whereas adding thinner gasket increased the compression ratio. The equation used for calculating the volume of head gasket is shown in Eq. (1).

$$\text{Head gasket vol.} = \frac{1}{4}\pi(\text{cylinder bore})^2 \times (\text{compressed thickness}) \qquad (1)$$

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2.3. Experimental procedure

At the onset, the engine was operated at low loading setup for around 10 to 15 minutes in diesel only approach to achieve steady state condition which was confirmed when there was no change in cooling water outlet and exhaust gas temperatures. All the recording of data were made after the steady state had reached and at the engine default injection timing (IT) of 23□A before top dead centre (bTDC) and constant speed of 1,500 rpm (± 20 rpm) for distinct load settings of 25, 50, 75 and 100%. At first, the engine was tested for diesel only approach at CR of 17.5 for different aforementioned loading conditions and results were recorded in a computer through the software provided for the engine test setup. For dual fuel approach with diesel and biogas as the pilot and primary fuels correspondingly, the engine was tested at different CRs of 16.5, 17, 17.5 and 18 for all the loading conditions. At the onset, the engine was operated with diesel for each CR configuration and the required load was applied through the loading panel. Then biogas was slowly inducted to the intake manifold through the venturi type gas mixture. Due to the induction of more amount of biogas, the engine speed briefly increased and it activated the fuel governing system to maintain the engine speed by reducing the diesel flow rate into the engine. The biogas induction was continued till the engine could achieve normal combustion. The engine was then made to run for several minutes till the speed was actually normalized. At this point, results were again recorded through the computer. Similar procedure was followed for all the loading conditions at different CRs in the dual fuel approach and results were recorded. Every test was repeated thrice each and the mean of the measured results were utilized for the analysis of characteristics of combustion, emissions and performance.

The uncertainty associated with the measured and the calculated quantities were computed using the methods expressed by Holman [36] and the results were found to be within the acceptable limits for experimentations.

Table 3 displays the accuracy and range of the instruments used for the experimentation.

Table 3. Accuracy and range of the experimental instruments/devices.

Instrument/Device	Make	Type	Accuracy	Range
Pressure sensor	Kistler	Piezoelectric	± 1 bar	0-100 bar
Water flow	-	Acylic body rotameter	- -	40-400 lph – engine 10-100 lph - calorimeter
Exhaust gas calorimeter	-	Shell and tube	-	-
Load indicator	-		± 0.1 kg	0-20 kg

Temperature sensor	-	K	± 1□	0-1500□
Flue gas analyzer CO CO_2 HC NO_x	Testo	Testo 350 portable	 ± 10 ppm ± 0.3% ± 10% ± 5%	 0-40,000 ppm 0-10,000 ppm 0-50% -vol 0-3,000 ppm
Dynamometer	Powermag	Strain gauge	-	0-50 kg
Speed sensor	-	PNP sensor	± 10 rpm	0-9999 rpm
Crank angle encoder	Kubler	Pulse	± 1□	0-360 ppr

3. Results and Discussion

presents the significance of different symbols used in the graphs of combustion, performance and emission analysis.

Table 4. Symbols used in the graphs.

Symbol	Significance
D, CR =17.5	Diesel only mode at CR of 17.5
B+D, CR = 18	Biogas and diesel dual fuel mode with diesel as pilot fuel at CR of 18
B+D, CR = 17.5	Biogas and diesel dual fuel mode with diesel as pilot fuel at CR of 17.5
B+D, CR = 17	Biogas and diesel dual fuel mode with diesel as pilot fuel at CR of 17
B+D, CR = 16.5	Biogas and diesel dual fuel mode with diesel as pilot fuel at CR of 16

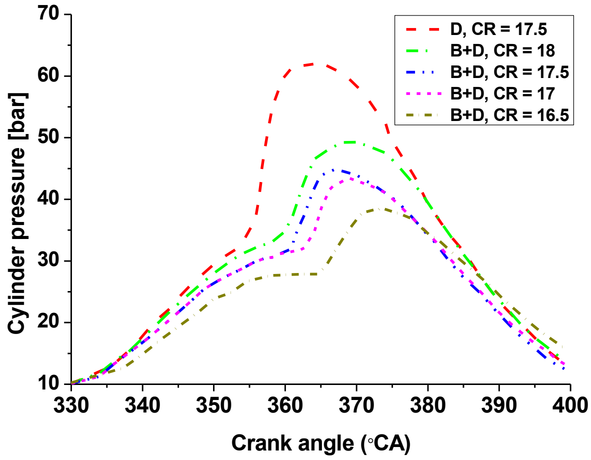

Fig. 3. Cylinder pressure as a function of crank angle for different CRs at full load.

3.1. Combustion analysis

3.1.1. Cylinder pressure

Variation of cylinder pressure with respect to crank angle for diesel only approach and dual fuel approach for different CRs at full load settings is shown in Fig. 3. The cylinder pressure was maximum at 61.93 bar at 364ºCA (degree crank angle) is witnessed for the diesel only approach in contrast to the dual fuel approach. It could be attributed to the reduction in combustion pressure due to a decrease in the charge temperature and flame speed owing to the presence of CO_2 during the induction of biogas in the dual fuel approach [18]. However, for the dual fuel approach, in cylinder pressure rises as CR is increased from 16.5 to 18. The maximum pressures of 38.47 bar, 43.46 bar, 44.9 bar and 49.3 bar were witnessed for the CR values of 16.5, 17, 17.5 and 18 correspondingly.

3.1.2. Net heat release rate

Fig. 4 displays the variation of net heat release rate with respect to crank angle for dual fuel and diesel only approaches for different CRs at full load settings is displayed The diesel only approach results in a higher net heat release rate of 81.36 J/ºCA as compared to the dual fuel approach as there is a delay in the ignition of biogas in the latter. Additionally, for the dual fuel approach, there is a slight increase in net heat rate when CR is increased from 16.5 to 18. The net heat release rates had peaks of 37.34 J/ºCA, 39.14 J/ºCA, 43.10 J/ºCA and 44.65 J/ºCA for the CR values, 16.5, 17, 17.5 and 18 respectively.

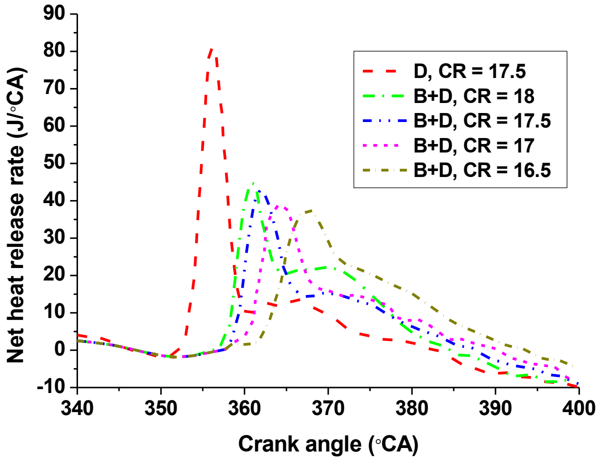

Fig. 4. Net heat release rate as a function of crank angle for different CRs at full load.

3.1.3. Ignition delay

Ignition delay may be described as the time in the middle of the onset of induction time and onset of combustion time. The dual fuel approach with biogas as primary fuel results in greater ignition delays for different CRs in contrast to the diesel only approach. This may be attributed to the incidence of biogas in large quantities in the intake thereby causing a decrease of the energy content of the air-fuel mixture in the dual fuel approach. Nevertheless, for the dual fuel approach, greater the CR, greater is the pressure and temperature of the combustible mixture of biogas and air towards the termination of compression [24]. It ultimately boosts the reactions of pre-ignition, thus influencing the injected pilot fuel ignition and hence results in a decrease in ignition delay with a rise in CR as shown in Fig. 5. Further, a gradual decline in ignition delay is detected as the engine load was raised from 25% to 100%.

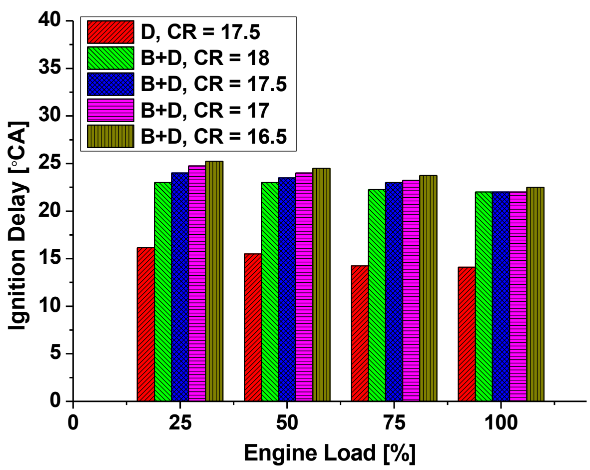

Fig. 5. Ignition delay as a function of engine load for different CRs.

3.2. Performance analysis

3.2.1. Brake thermal efficiency

Fig. **6** presents the brake thermal efficiency (BTE) as a function of engine load for different CRs. BTE was highest for the neat diesel approach for all the load ranges as compared to the biogas dual fuel approach at various CRs and loads owing to the lesser calorific value and flame speed cause by biogas presence in the dual fuel approach. Further, in the dual fuel approach, the BTE increased as CR was increased and loading which may be attributed to higher cylinder caused by increase in engine load. The maximum BTEs for the dual fuel approach observed at full load for CRs 18, 17.5, 17 and 16.5 were found to be 21.74%, 20.41%, 18.87% and 17.24% respectively.

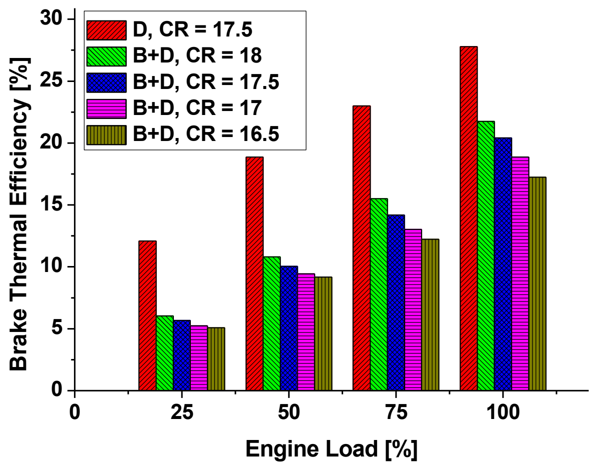

Fig. 6. Brake thermal efficiency as a function of engine load for different CRs.

3.2.2. Volumetric efficiency

The diesel only approach resulted in the highest volumetric efficiency when compared with the dual fueling with biogas due to the fresh air displacement by biogas in the dual fuel approach. The volumetric efficiency decreased with increasing loading condition under both diesel only and biogas-diesel dual operations, as can been seen from Fig. 7. An increase in CR, the volumetric efficiency improved marginally in dual fuel approach for all the load ranges. The maximum volumetric efficiencies were found to be 77.92% and 84.15% for the dual fuel and diesel operations at CR 18 respectively, at 25% engine load.

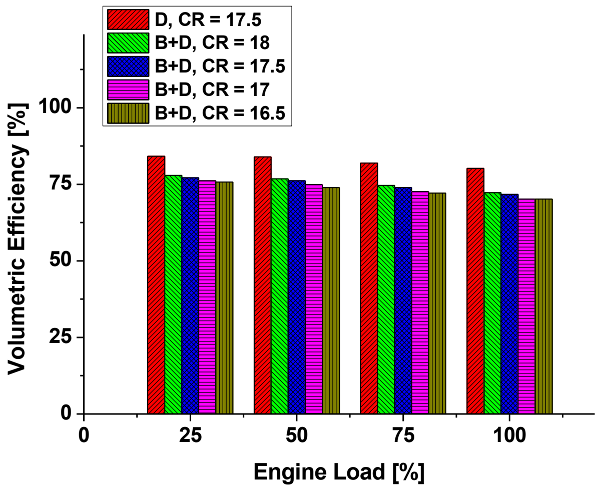

Fig. 7. Volumetric efficiency as a function of engine load for different CRs.

3.2.3. Exhaust gas temperature

A plot of exhaust gas temperature (EGT) variation with the engine loads for both the diesel only approach and dual fuelling approach at different CRs is displayed in Fig. 8. The EGT of the diesel only approach manifested a lesser value through the engine load variations in contrast to the dual fuel approach. Further, in the biogas dual fuelling method, the EGT rose with increase in engine load while manifesting a decline with increase in CR. Under full load setting, the EGT of the dual fuel approaches are maximum for the different CRs viz., 346ºC, 364ºC, 367ºC and 378 ºC at CR values 18, 17.5, 17 and 16.5 correspondingly.

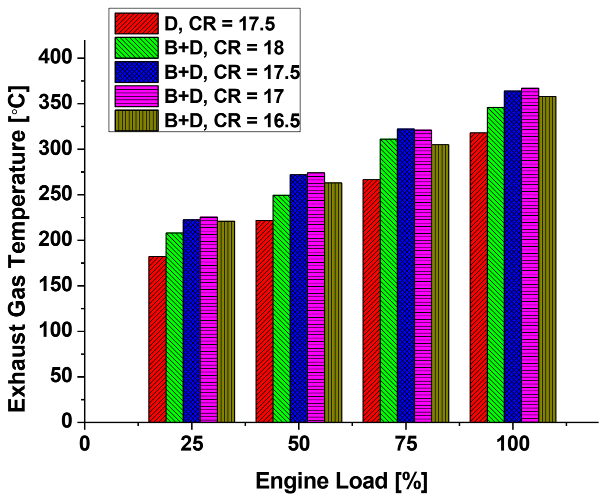

Fig. 8. Exhaust gas temperature as a function of engine load for different CRs.

3.2.4. Brake specific energy consumption

Diesel only approach manifested the least brake specific energy consumption (BSEC) as compared to the biogas dual fuel approach, as displayed in Fig. 9. The BSEC dropped with increasing load for both the approaches. Considering a given load setting for a dual fuel approach, the BSEC also dropped with rising CRs. The least BSEC for dual fuel approach was observed to be 4.6 kJ/s /kW for CR of 18 at 100% engine load.

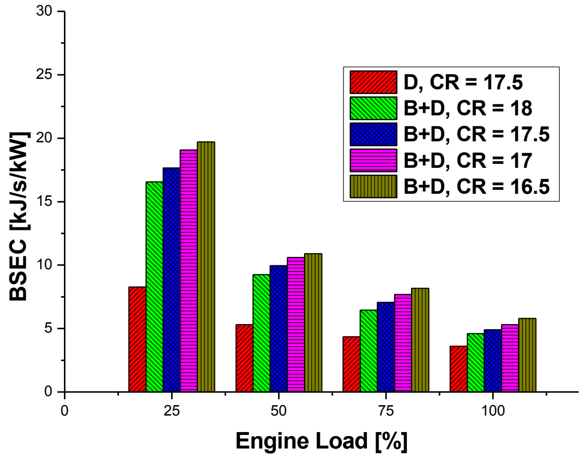

Fig. 9. BSEC as a function of engine load for different CRs.

3.3. Emission analysis

3.3.1. Hydrocarbon emission

The HC emissions with respect to engine loads is shown in Fig. 10. Comparatively, the HC emissions of diesel approach is much lesser than those of dual fuel approach for all the CRs which is caused by the poorer characteristics of combustion of biogas due to the presence of diluents like CO_2 in the dual fuel approach. Additionally, with a rise in CR, there is a decline in emissions of HC for the dual fuel approach due to an improvement in combustion characteristics. The worst HC emission is recorded as 317 ppm at CR of 16.5 under full load setting in the dual fuel approach.

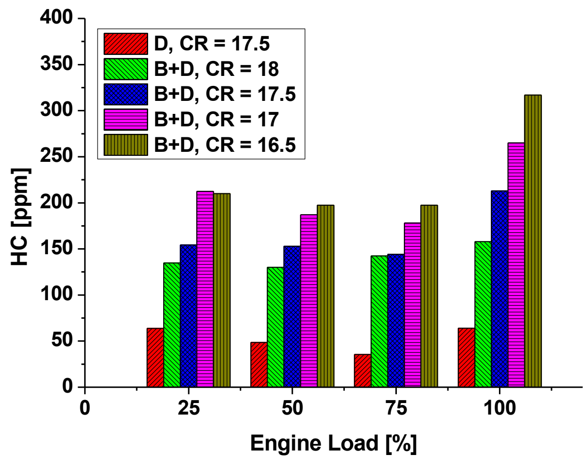

Fig. 10. Emission of hydrocarbons (HC) as a function of engine load for different CRs.

3.3.2. Oxides of nitrogen emission

The diesel only approach manifests a comparatively huge amount of emission of oxides of nitrogen in contrast to the dual fuel approach as presented Fig. 11. In-cylinder temperature and pressure is higher in diesel only approach, which leads to greater formation of NO_x whereas in dual fuel approach, lower flame velocity along with presence of diluents in the biogas results in lower combustion temperature leading lesser production of NO_x . As the load of the engine was incremented, both the dual fuel and diesel only approaches result in increase in NO_x emissions. Considering the dual fuel approach, a rise in NO_x emissions is also manifested with an increment in CRs for all the engine loads. Greater the CR, greater is the in-cylinder temperature that results in greater NO_x formation. The highest NO_x emissions is recorded as 69 ppm at CR of 18 under full load setting of dual fuel approach.

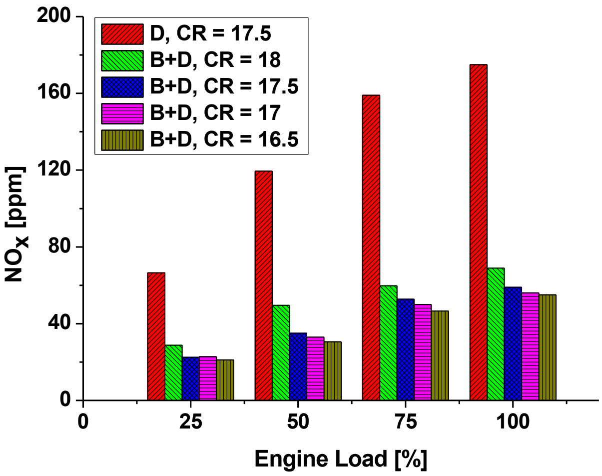

Fig. 11. NO_x emission as a function of engine load for different CRs.

3.3.3. Carbon dioxide emission

The emission of CO_2 manifests an increase with an increment in engine loads for both the dual fuel and diesel only approaches as shown in Fig. 12. However, the emission of CO_2 is greater in the dual fuel approach due to its inherent occurrence of CO_2 in the biogas in contrast to the diesel only approach. Under the dual fuel approaches, for higher loads, there is higher consumption of biogas and hence increase in CO_2 emissions. Moreover, with the rise in CR, the emission of CO_2 also increases. The worst CO_2 is recorded as 3.9% at CR of 18 under full load setting.

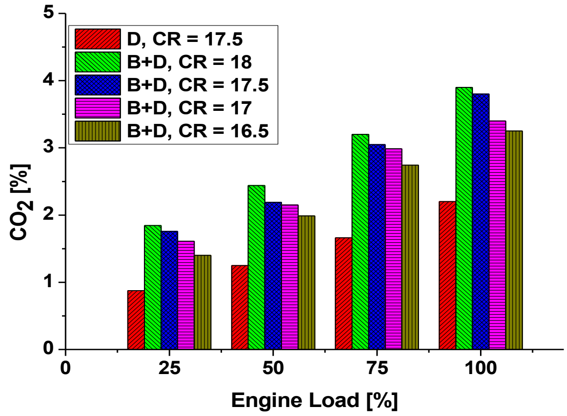

Fig. 12. CO_2 emission as a function of engine load for different CRs.

3.3.4. Carbon monoxide emission

The emission of CO is relatively lower in diesel only approach in contrast to the dual fuel approach as presented in Fig. 13 owing to the incomplete combustion of the combustible biogas air mixture caused by the charge dilution by CO_2 in dual fuel approach. Under the dual fuel approach, with an increment in CR, the emissions of CO declines for the entire engine loads due to enhancement in combustion characteristics. However, with an increment in engine load, the emission of CO reduces on an average.

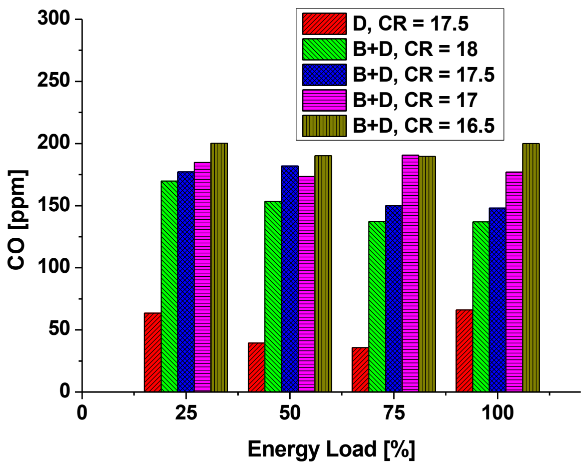

Fig. 13. CO emission as a function of engine load for different CRs.

4. Conclusion

A research investigation was implemented to analyse the influence of compression ratio on the characteristics of emissions, performance and combustion of a CI engine dual fuelled with diesel and biogas as the pilot and primary fuels respectively. From the experimental results, the subsequent conclusions can be reached:

1. The maximum BTEs for the dual fuel approach observed at full load for CRs 18, 17.5, 17 and 16.5 were found to be 20.1%, 18.2%, 16.4% and 16.2% respectively.
2. In comparison with the diesel only approach, for the dual fuel approach, the ignition delay is greater owing to the reduction in charge temperature and the high specific heat capacity of biogas.
3. Diesel only approach results in lower BSEC than the dual fuel approach. However, the least BSEC for dual fuel approach was observed to be 4.6 kJ/s/kW for CR of 18 at 100% engine load.
4. Dual fuel approach resulted in greater enhancement of NO_x emissions in contrast to diesel only approach for all the load range owing to the higher in-cylinder temperature and pressure in diesel only approach and lower flame velocity along with presence of diluents in the biogas resulting in lower combustion temperature in dual fuel approach.
5. The emissions of CO and HC however, are relatively lower in diesel only approach in contrast to the dual fuel approach due to the presence of diluents like CO_2 in the biogas used in dual fuel mode. Additionally, with an increase in CR, there is a decline in emissions of HC and CO for the dual fuel approach due to an improvement in combustion characteristics.
6. An overall superior characteristic of combustion, emissions and performance is manifested by CR of 18. Nevertheless, it resulted in higher emissions of CO_2 and NO_x in contrasts to the other CRs.

The diesel only approach shows better performance and emission as compared to dual fuel approach except for NO_x emissions for all the load settings. The result from the investigation manifested the effective usage of biogas in the CI engine employing higher CR as improvement of performance and emission with an increase in CR is observed. An improvement in the quality of the biogas may lead to better performance and emission characteristics of the CI engine.

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