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Effect of Compression Ratio on the Performance of a Constant Speed Spark Ignition Engine Operating on Raw Biogas

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ABSTRACT

In the present investigation, experiments were conducted in a 4.4 kW, single cylinder, water cooled, constant speed, spark ignition (SI) engine fuelled with raw biogas. The engine was operated at four different compression ratios (10.52, 11.94, 13.96 and 15.29) and within a load range of 6 to 77%. The effect of load level on the performance and emission characteristic of the engine at different compression ratios are analysed and presented in this paper. The brake power producing capability of the engine corresponds to CR 15.29 was maximum and found to be 2.93 kW with 76.27% of brake load. With increasing CR the engine becomes more stable and operates with an appreciable deviation in speed. Irrespective of engine loading condition, the minimum HC and CO emissions were noticed at CR 15.29 and found to very between 23-144 ppm and 0.016-0.091 %, respectively. The maximum NOx emission was detected at CR 15.29 and was found to very between 27-240 ppm.

1. Introduction

The increasing concern of energy security and environmental protection has stimulated the active research on improving fuel economy and reducing exhaust emission. To address this issues, the major research aspects of combustion and engine development has attracted the development of alternative fuelled engines. Liquid fuels like alcohols and vegetable oils, gaseous fuels such as natural gas, liquefied petroleum gas (LPG), hydrogen, biogas, and producer gas are promising alternative fuels [Chandra et al., 2011]. Very low levels of pollutant emission were reported when gaseous fuels are effectively utilized in spark ignition (SI) and compression ignition (CI) engines [Porpatham et al., 2012]. Gaseous fuels are quite acceptable for IC engine because of their wider range of flammability limit, higher hydro carbon ratio and capability to form homogeneous mixture [Porpatham et al., 2013, 2008]. Biogas is one such a renewable fuel and attractive source of energy produced from anaerobic digestion of organic matters. It consists of approximately 50-70% of methane (CH_4), 25-50% of carbon dioxide (CO_2), 1-5% of hydrogen (H_2), 0.3-3% of nitrogen (N_2) and traces of other impurities, notably hydrogen sulfide (H_2S) [Nathan et al., 2010, Hotta et al., 2015]. Typically, it consists of 60% of CH_4 and 40% of CO_2 [Crookes et al., 2006, Hung et al., 1998]. The auto ignition temperature of biogas is very high, hence, it resist knocking which is desirable in SI engine [Porpatham et al., 2008, 2012 and 2013]. Since biogas has a higher anti nock index, biogas fueled SI engine can sustain high compression ratio (CR), which enhances the thermal efficiency of the engine [Porpatham et al., 2007].

The performance and efficiency of a SI engine is mainly dependent on the combustion phasing and is influenced by factors such as compression ratio (CR), spark advance (SA) or ignition advance (IA), air-fuel ratio (AFR), exhaust gas recirculation (EGR), variable valve timing (VVT), combustion chamber design and composition of the fuel [Alagumalai et al., 2014, Corti et al., 2014]. Out of which CR is the most important parameter for optimizing the efficiency, emission and permitting combustion engines to conform future emission targets and standards. Proper control of ignition advance timing and CR can significantly improve the exhaust emission and the performance parameters for various kinds of operating fuels in IC engines [Mitzlaff, 1988]. Increased compression ratios is an effective means of increasing the performance of biogas fueled engine when CO_2 is present in the biogas. However, the break mean effective pressure and break thermal efficiency increases steadily with compression ratios up to a critical value of 13:1 [Huang et al., 1998]. Operating with a variable compression ratio (VCR) Ricardo E6 single cylinder SI engine fueled with simulated biogas Hung and Crooks reported the effect of compression ratio with RAFR and carbon dioxide fraction of 0.97 and 37.5%, respectively. As reported break mean effective pressure (BMEP) and break thermal efficiency (BTE) values increase steadily with compression ratio up to a critical value of 13:1, above which there is a slight increase in these values. Although there is a slight increase in the BMEP along with the increase in the CR above 13:1, the additional indicated power (IP) do not compensate the mechanical losses arises due to friction. The traces of detonation were also observed at CR 15:1 [Surata et al., 2014]. In case of biogas fueled engine, the CR that can be

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employed should be higher than normal SI engine as the CO_2 present suppresses the knock. CR ranging from 11:1 to 13:1 reported suitable for operation without knock [Porpatham et al., 2008]. SI engine operated with biogas contains significant amount of CO_2 and N_2 which decreases the performance and increases the NOx emission as compared with natural gas and gasoline fueled engine [Kapdi et al., 2005].

In view of the current demand of energy utilization, fuel crisis, waste to energy conversion techniques and search of renewable resource of energy, the use of raw biogas as a standalone fuel in SI engine seems to be a good alternative solution. In order to make the raw biogas fueled SI engine more energy efficient, a detail investigation has been carried out to understand the effect of CR on the performance, combustion and emission characteristics of raw biogas fueled SI engine operating with a CR ranging from CR 10.52 to CR 15.29.

2. Experimental Details

2.1 Selected fuel and their properties

The raw biogas selected for the evaluation of the engine performance was produced by anaerobic digestion of cow dung and lignocellulos biomass in a Dinabandhu modeled biogas digester of 3 cubic meter capacity. The biogas produced from the digester was collected and stored in a neoprene coated rubber fabric balloons connected in series. The stored biogas is then supplied to the engine by flexible pipes. The composition of the used fuel is analyzed each time before testing by Thermo Fisher Scientific make gas chromatograph (GC). It has been observed that there is no substantial change in the composition of the produced biogas unless until there is drastic change in environmental operating parameters or change in feed materials to the biogas digester. However, there is a little variation in the composition of the biogas with time according to the activities of the anaerobic bacteria. Table 1, describes the composition and some of the important properties of biogas used in the experiment.

Table 1. Properties of the used fuel

Properties	Biogas
Composition	CH_4-55.6%#, CO_2- 42.3# N_2- 2.1#
Density at 15^{0}C (kg/m3)	1.11#
Lower heating value (MJ/kg)	17#
Heat of vaporization (MJ/kg)	0.5
Stoichiometric A/F ratio	5.67*
Research octane number	110 [12]
Auto ignition temperature (^{o}C)	650 [12]
Flame Speed (cm/s)	25 [12]

* Calculated # Experimental value

2.2 Experimental engine test rig

The experimental setup shown in Fig. 1 consists of a Prakash made single cylinder, 990.6 CC, four stroke, water-cooled, constant speed, SI engine of rated power and speed of 4.4 kW and 1500 rpm, respectively. The engine was equipped with a unique governing system and a T-type mixture along with two throttle valve to control the mass flow rate of air and air-biogas mixture (as shown in Fig. 2) at all operating load to maintain the engine speed constant. The engine was coupled with a single phase, 3.5 kVA alternator to generate 230 V and 50 Hz frequency at 1500 rpm. For loading the engine crank shaft the output of the alternator was connected with a load panel consisting of 15 numbers of 200 Watt bulbs in series. To track the consumed current and output voltage of the alternator at a particular loading condition of the engine a voltmeter and an ammeter was connected inline before the load panel. The rated CR of the engine was 13.94 for biogas mode operation. But for the sake of analyzing the effect of CR on the performance and emission characteristics of a biogas fuelled constant speed SI engine, the CR ratio of the engine was varied manually by altering the clearance volume of the engine. Since the stroke volume (939.69 CC) and the piston cavity (51 CC) were known, the engine CR without any clearance slot was found to be 19.38. Therefore by adding copper slots of 2.65 mm thick and bakelite slots of 1.8 mm thick at different combinations the CR of the engine was varied for each test. The performance tests of the engine were conducted at four different CRs i.e., CR 10.52, CR 11.96, CR 13.94 and CR 15.29. The engine was well instrumented to track down the operating parameters. The load on the engine was varied by applying electrical load on the alternator. For measuring the biogas flow rate a biogas flowmeter (make: Siya Instruments, Model SI-6) was used. An air box was fabricated along with an orifice of 20 mm diameter and connected with an open U tube manometer; the pressure difference in the manometer column was later used to calculate the air mass flow rate. A diaphragm type piezo pressure sensor along with built in amplifier and no noise cable was mounted on the engine head to measure the cylinder pressure during combustion. The optical crank angle encoder attached to the engine delivers a signal for each degree rotation of the crankshaft. The pressure and crank angle signals are then interfaced to the computer through piezo power unit to observe the pressure and crank angle signals as well as to measure the speed of the engine. The engine is connected to the Labview based software "Enginesoft" to record and analyze the data stored via a NI USB 6210 data logger. The emission analysis is carried out by using AVL DIAGAS 444N five-gas analyzer.

3. Results and Discussions

The performance and emission characteristics of a constant speed biogas fueled SI engine were evaluated for varying load conditions at four different compression ratios ranging from CR 10.52 to CR 15.29. The effect of compression ratio on the performance, and emission characteristics of the raw biogas fuelled SI engine were analysed carefully throughout the operating load range and explained in the below mentioned sections.

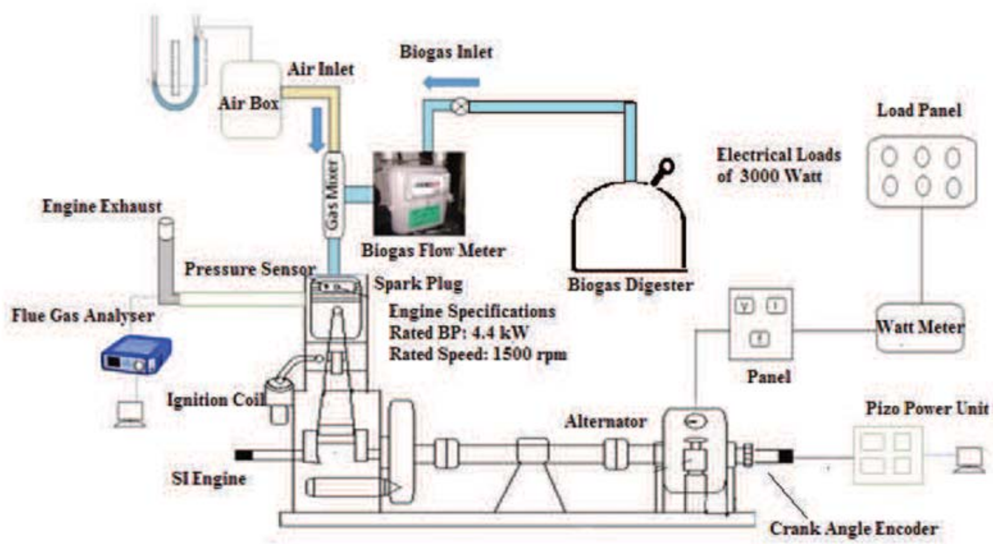

Fig. 1 Schematic layout of experimental test rig

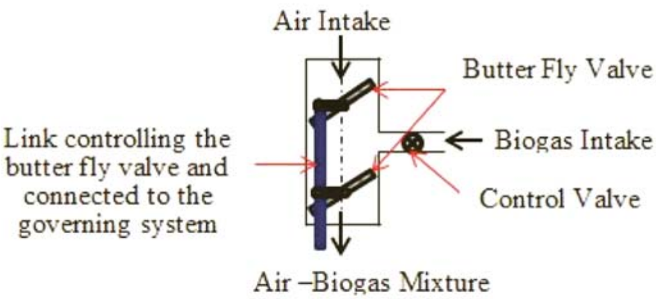

Fig. 2 Air intake and fuel mixing system

3.1 Performance analysis

Figure 3 shows the correlation between brake load (%) and brake power (BP) (kW) developed by the raw biogas fuelled SI engine operated with compression ratios of 10.52, 11.96, 13.94 and 15.92. The spark timings for each compression ratios were set to MBT before conducting each test. As observed, irrespective of the CR, the BP developed by the engine was increasing with progressive development of the brake load on the engine. Since the developed speed of the engine irrespective of CRs are almost constant, the developed brake torque will increasing with increasing brake load, as a result of which BP of the engine will increase with progressive development of brake load on the engine. As shown in Fig. 7 and 8, with increasing brake load, the mass flow rate of the fuel consumed and the volumetric efficiency of the engine are increasing to maintain the rated speed of the engine constant. This may be the key reason for increasing BP with increasing brake load on the engine. It was also observed that with increasing CR the maximum BP output of the engine was increased along with enhanced brake load carrying capacity of the engine. Higher CR increases the mean gas temperature (MGT) and initiates the complete combustion and leads to higher energy conversion efficiency and develops more power.

The maximum and the minimum BP output of the engine were noticed at CR 15.29 and CR 10.52, respectively. The maximum brake power output of the engine operated at CR 10.52, CR 11.96, CR 13.94 and CR 15.29 were found to be 1.94, 2.82, 2.88, and 2.93 kW with maximum brake load development of 50.40%, 73.33%, 74.80% and 76.27%, respectively. Increasing the CR from CR 10.52 to CR 11.96, CR 11.96 to CR 13.94 and CR 13.94 to CR 15.29 increases the maximum BP output of the engine by 45%, 2%, and 1.95% respectively. However, the observed power reduction of the engine when operated with raw biogas were found to be 55.9%, 35.9%, 34.5% and 33.4% at CR 10.52, CR 11.96, CR 13.94 and CR 15.29, respectively. Similar results have been reported by R. Chandra et al., (2011) and Kapdi, S. S (2005), the power reduction of a CI engine when converted to a biogas fuelled SI engine was found to 46.3% at CR 12.65.

The variations of the engine speed developed by the biogas fuelled SI engine operated at different CRs are shown in Fig. 4. It was observed that with progressive development of the engine load the speed of the engine starts deviating from its rated speed. However, these deviations are quite acceptable in CR 15.29, CR 13.96 and CR 11.94 where, the maximum deviation is only 9.3% from the rated speed. It was noticed that at CR 15.29, CR 13.96 and CR 11.94 the engine speed remains almost constant (1500±50 rpm) up to 50% of the developed brake load and starts deviating after wards. The reason that could fit to explain the above happening may be the inefficiency of the governing system attached to the engine, which could not supply the accurate air-fuel mixture to the engine beyond 50% engine load. But, at CR 10.52% the engine speed was found decreasing with increasing brake load on the engine. However, the minimum speed observed was 1128 rpm at 50% engine load and was the maximum developed brake load at CR 10.52. Similar trend was also noticed by R. Chandra et al., (2011). With increasing CR the engine becomes more stable and operated with an appreciable deviation in speed.

Figure 5 shows the correlation between the brake specific fuel consumption (BSFC) and brake load of the biogas fuelled SI engine at different operating CRs. It was evident from the figure that, irrespective of CR, the brake specific fuel consumption follows a decreasing trend along with the increasing brake load of the engine. This is because, with increasing brake load, the rate of rise in BP is higher than the rate of rise in mass of fuel consumed. It was also observed that the BSFC of the engine follows a decreasing trend along with progressive development of the operating CR. The biogas engine operated at CR 15.29, CR 13.94, CR 11.96 and CR 10.52 showed the maximum BSFC of 5.29 kg/kWh, 5.17 kg/kWh, 5.83kg/kWh and 5.53 kg/kWh at the brake loads of 13.8%, 15.20%, 13.8% and 14.57%, respectively. However, the minim BSFC of the engine operated at CR 15.29, CR 13.94, CR 11.96 and CR

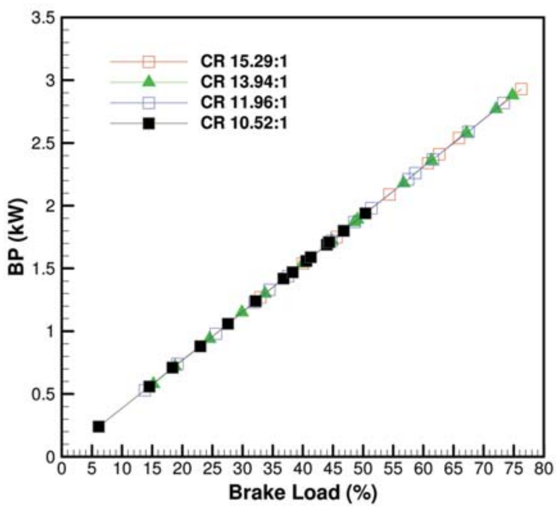

Fig. 3 Effect of CR on the BP developed by the engine

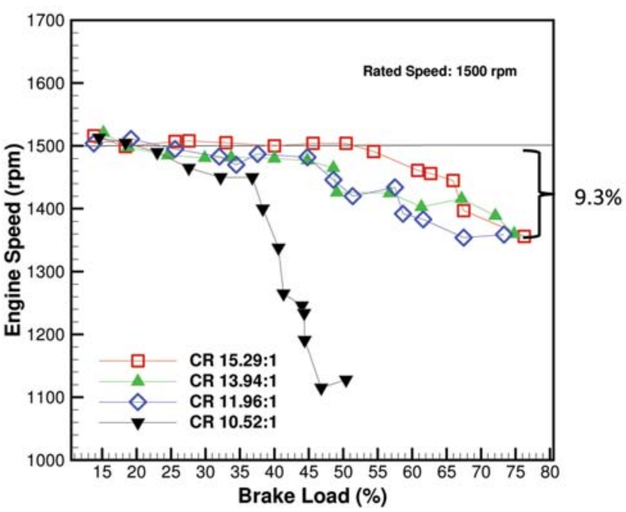

Fig. 4 Effect of CR on the developed speed of the engine

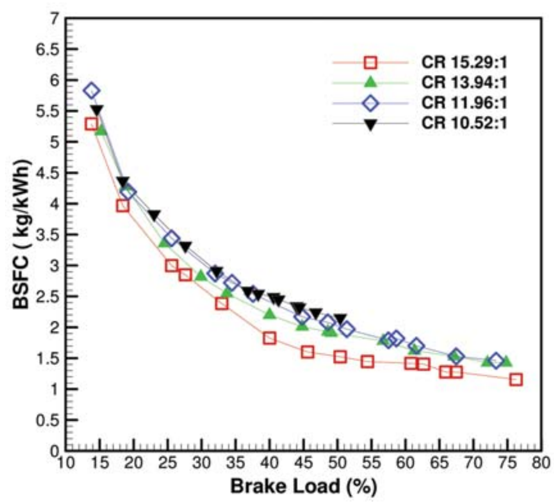

Fig. 5 Effect of CR on the BSFC of the engine

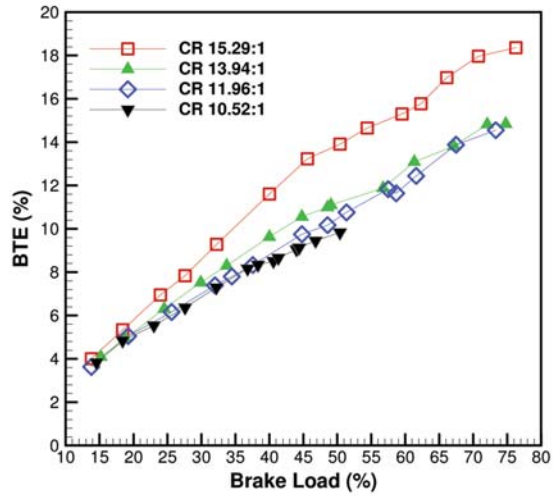

Fig. 6 Effect of CR on the BTE of the engine

10.52 are found to be 1.15 kg/kWh, 1.43 kg/kWh, 1.46 kg/kWh and 2.15 kg/kWh at the brake loads of 76.2%, 74.8%, 73.3% and 50.4%, respectively. At a particular loading condition (50% brake load) increasing the CR form 10.52 to 11.96, 11.96 to 13.94 and 13.94 to 15.29 reduced the BSFC by 8.37%, 4% and 21%, respectively. This because, with increasing CR, the rate of rise in BP is lesser than the rate of drop in mass of fuel consumed and the mass fuel consumed to generate unit BP is comparatively lesser than at lower CRs. Hence, The BSFC is reduced with increased CR.

The variation of brake thermal efficiency (BTE) of the engine along with progressive advancement of the developed brake load at different operating CRs are shown in Fig. 6. It was observed that, irrespective CR the BTE of the engine follows an increasing trend along with increasing brake load of the engine. Since, at all operating CRs the BSFC of the engine follows a decreasing trend against the developed brake load of the engine; the BTE is following an opposite trend. It was also observed that the BTE follows an increasing trend along with increasing compression ratio of the engine. This is because; along with increasing CR the BP of the engine increases and decreases the fuel consumption rate. The engine operated at CR 15.29 showed the maximum BTE of 18.35% at 76.2% of developed brake load. However, the maximum brake thermal efficiencies of the engine operated at CR 13.94, CR 11.96 and CR 10.52 are found to be 14.84%, 14.55% and 9.83%, respectively. Increasing the operating CR from 10.52 to 11.96, 11.96 to 13.94 and 13.94 to 15.92 enhanced the BTE of the engine by 48%, 2% and 23.6%, respectively.

Figure 7 shows the variation of the volumetric efficiency of the biogas fuelled SI engine against the developed brake load when operated with in CR ranging from 10.52 to 15.29. It was observed that, irrespective of CR, the volumetric efficiency of the engine follows an increasing trend along with progressive development of the engine load. This is due to the fact that along with increasing brake load, mass flow rate of fuel consumed is being increased which interns induce more air to combustion chamber. It was also observed that with along with increasing CR the volumetric efficiency of the engine follows a decreasing trend. The volumetric efficiencies of the engine operated at CR 10.52, CR 11.96, CR 13.94 and CR 15.29 are found to very between 34.6-51.1%, 32.7-48.8%, 29.1-48.3%, and 28.7-32.7% respectively. The maximum volumetric efficiency was observed at CR 10.52.

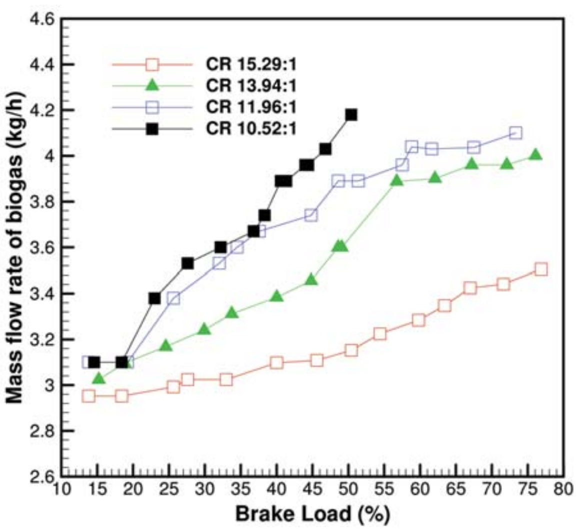

Fig. 7 Effect of CR on the fuel consumption rate

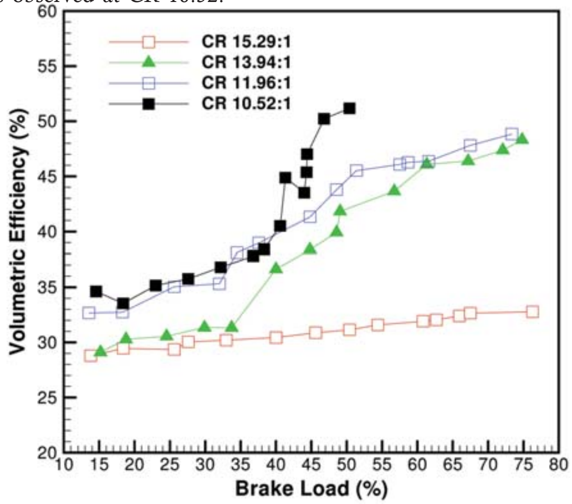

Fig. 8 Effect of CR on the volumetric efficiency of the engine

3.2 Emission analysis

Carbon monoxide (CO) forms partially due to deficiency of oxygen in the fuel air mixture leading to incomplete combustion. In the current investigation as depicted in Fig. 9 the CO emission decreases with increasing CR of the engine. The reason that could fit may be the increased amount of fuel mass consumed at lower CRs, which could not burnt completely due deficiency of oxygen and do not allow the CO to be oxidized. However, with increasing CR the flame front propagation becomes faster and consumes enough biogas-air mixture to bring down the CO level. It was also observed that, the CO emission follows an increasing trend along with progressive development of brake load of the engine. The minimum CO emission was observed at CR 15.29 and found to very between 0.016 to 0.091%. The maximum CO emission was found at CR 10.52 and very between 0.022 to 0.17%.

The variation of hydrocarbon emission at different CRs of the biogas fuelled SI engine is shown in Fig. 10. It was observed that HC content in exhaust emission of the biogas fuelled SI engine was decreased with increased CR of the engine. It was also observed that with increasing brake load the HC emission was increased. Irrespective of engine loading condition, the minimum HC emission was observed at CR 15.29 and was found very between 23-144 ppm.

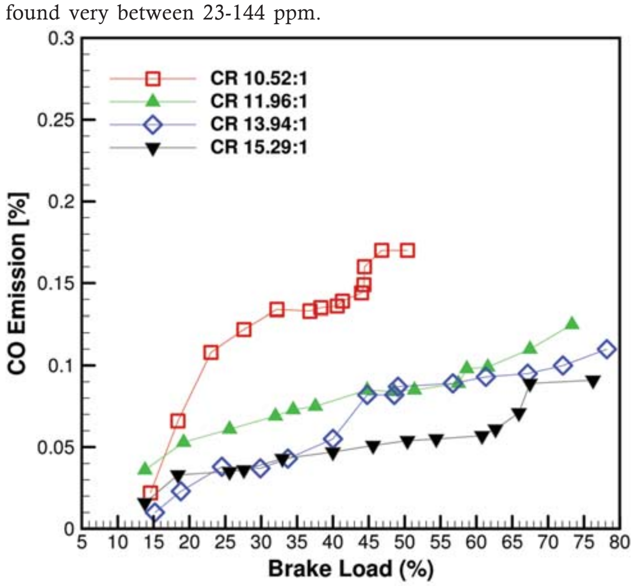

Fig. 9 Effect of CR on the carbon monoxide emission of the biogas fueled SI engine

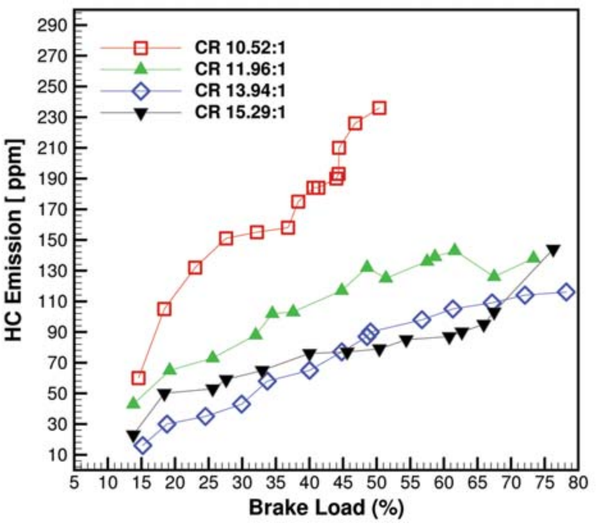

Fig. 10 Effect of CR on the hydrocarbon emission of the biogas fueled SI engine

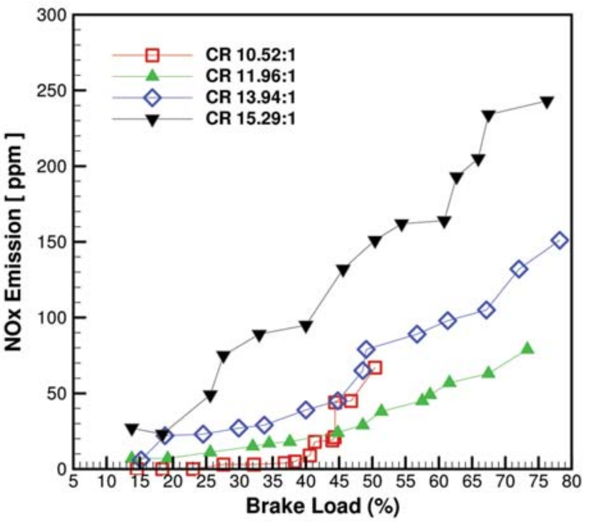

Fig. 11 Effect of CR on the nitric oxide emission of the biogas fueled SI engine

Figure 11, shows the effect of compression ratio on the NO_x emission of a biogas fuelled SI engine. It was observed that with increasing CR and brake load on the engine the NO_x concentration in the exhaust emission of the biogas fuelled SI engine follows an increasing trend. The maximum NO_x emission was detected at CR 15.29 and was found to very between 27-240 ppm. The NO_x emission is strongly related to the lean fuel with high cylinder temperature or high combustion temperature. The cylinder temperature and combustion temperature increases with increasing CR and is higher in case of CR 15.29 as compared to other CRs. Because of this reason only the NO_x concentration is comparatively higher in CR 15.29.

4. Conclusions

Based on the experimental investigation carried out to investigate the effect of CR on the performance and emission characteristics of the raw biogas fueled, constant speed SI engine, the following conclusions are drawn.

Higher CR increases the mean gas temperature MGT and initiates the complete combustion which leads to higher energy conversion efficiency and develops more power.

With increasing CR the maximum BP output of the engine was increased along with enhanced brake load carrying capacity of the engine. With a maximum brake load development of 76.27%, the brake power output of the engine was found maximum (2.93 kW), when operated at CR 15.29. With increasing CR the engine becomes more stable and operated with an appreciable deviation in speed. he biogas engine operating with CR 15.29 revealed the minimum BSFC (1.15 kg/kWh) and the maximum BTE (18.35%) at 76.2% of brake load.

The CO and HC concentration in the exhaust emission decreases with increasing CR of the engine. The minimum CO and HC emission were observed at CR 15.29 and found to very between 0.016 to 0.091%. and 23-144 ppm, respectively. With increasing CR and brake load on the engine the NO_x concentration in the exhaust emission of the biogas fuelled SI engine follows an increasing trend. The maximum NO_x emission was detected at CR 15.29 and was found to very between 27-240 ppm.

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