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Effects of Varying Injection Timing on Performance and Emission Characteristics of Dual Fuel Engine Fueled with Biogas

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Abstract: In this study, the influence of injection timing on the performance and exhaust emissions of a naturally aspirated, single cylinder, diesel engine running on dual fuel mode has been experimentally investigated. Diesel was used as a pilot fuel and biogas was inducted at an optimum flow rate of 0.9 kg/h along with the air in suction. The tests were conducted at four different injection timings 23o, 24.5o, 26o and 27.5° CA bTDC. The experimental results showed that, the BSEC (brake specific energy consumption) in the dual fuel opera-tion was found to be higher than that of diesel operation at full load. A reduction in the NO and smoke emissions were observed, whereas the HC and CO emissions were increased with advanced injection timing. The performance and the emission parameters of the en-gine running with biogas in the dual fuel operation at different injection timings were evaluated, compared with diesel operation and presented in this paper.

Keywords: *Dual Fuel, Biogas, Injection Timing, Performance, Emission.*

◆

Introduction

Increasing fuel price and stringent emission legislations are the two major challenges for the wider operation of compression ignition (CI) engines. In this respect, researchers focus on high efficiency and low emissions technologies. Among various emission reduction methods proposed, the use of gaseous fuels in the CI engine is a promising one [1-4]. However, in diesel engine simultaneous reduction of NOx and smoke still remains a major problem due to governing combustion mechanisms. Various new methods have been proposed to reduce the exhaust emissions by avoiding the combustion regions where the NOx and smoke are mainly generated [5-7].

Among gaseous fuels biogas is a promising alternate fuel. It is produced from the anaero-bic digestion of organic matters, which are found in abundance on earth and at a very cheaper price than that of gasoline and diesel. The main constituent in biogas is methane, which has a short carbon chains and thus helps in reducing greenhouse gases, thereby curbing global warming. Biogas has a higher hydrogen-to-carbon ratio than that of diesel results in reduced carbon dioxide emission and has an inherent clean nature of combustion. In addition, biogas has a better resistance to knock due to high octane number, which makes it suitable for high compression ratios engines [8]. Biogas has a disadvantage of having a very high auto ignition temperature. This inherent characteristic demands for a high energy source such as pilot fuel injection to achieve ignition in the combustion cham-ber. Biogas, with its properties presents a strong prospect in dual fuel CI engines. In dual fuel operation, during compression stroke, the compressed gaseous fuel-air mixture is ig-nited by the pilot injection of small amount of diesel through the conventional diesel fuel system [9].

In dual fuel operation, the fuel injection timing is one of the most important parameters determine the performance and emission characteristics of the engine. Fuel injection tim-ing plays a vital role in ignition delay and combustion characteristics of the engine, as the temperature and pressure change significantly close to the top dead centre (TDC). With early injections, there is increase in ignition delay due to lower initial air temperature and pressure. On the other hand, due to late injections, there is decrease in ignition delay be-cause of marginal increase in initial air temperature and pressure [10-17]. Parlak et al. [18] studied the influence of injection timing on the NOx emission and brake specific fuel con-sumption (BSFC) of a low heat rejection (LHR) indirect injection diesel engine using die-sel fuel. They conducted the tests with variable loads at engine speeds of 1000, 1400, 1800 and 2000 rpm and the static injection timing of 38° , 36°, 34° and 32° crank angles (CA). Initially, they conducted the load tests on original diesel engine and later adopted for LHR engine. The experimental investigation showed that NOx emission increased by about 15% when LHR was operated at injection timing of 38° CA before top dead centre (BTDC), which happened to be the optimum value of the original engine. However, at 34° CA re-tarded injection timing, there was decrease of about 40% in exhaust emissions and about 6% BSFC compared to that of the original diesel engine [19].

Another study by Nwafor [20] investigated the effect of advanced injection timing on the performance and exhaust emission in a dual-fuel CI engine primarily fuelled by natural gas. The injection timing was advanced by 3.5° (i.e . 33.5° CA BTDC) where original in-jection timing was 30° CA BTDC. The results of the investigation on the dual-fuel engine indicated that there was a significant increase in the percentage of hydrocarbon (HC) emis-sions compared to that of pure diesel fuel. However, while running the engine at advanced injection timing, a significant reduction in CO and CO2 were observed. On the other hand, there was a marginal increase in BSFC and decrease in break thermal efficiency (BTE) [21].

The objective of this study is to investigate the effects of varying injection timing on the performance and emission characteristics of dual fuel engine fuelled with biogas. The tests were conducted at different injection timings by changing the thickness of shims used in fuel injection pump. Moreover, to make study more meaningful, the investigation was carried out on the same engine. For the engine under experimental consideration, its perform-ance and emission characteristics were evaluated, analyzed, compared with diesel operation and presented in this paper.

I.Material and Method

A. Production of biogas

The biogas was generated in a floating dome digester by the anaerobic digestion of pon-gamia pinnata (Karanja) de-oiled cake. The gas was collected in a gas holder and was taken to the engine by a hose pipe (diameter: 12mm). The concentration of methane, car-bon dioxide, carbon monoxide, hydrogen sulphide etc. was measured using a non- dispersive infrared biogas analyzer. The flow rate of biogas to the engine at each operating condition was measured with the help of a biogas flow meter (Make: Siya, Model: SI10) attached before the mixing kit in the intake manifold. A perforated gas mixing kit was at-tached to the intake manifold for ensuring proper air and biogas mixture supply to the en-gine.

B. Test fuel properties

Diesel was used as an injected fuel into the combustion chamber for initiating the combus-tion and the properties of diesel are given in Table 1.The biogas obtained by the anaerobic digestion of Karanja de-oiled cake was characterized to find the physical properties and elemental composition. The main constituents in biogas obtained from the analysis are given in Table 2 and the different properties of biogas are given in Table 3.

Table 1 Properties of diesel.

Properties	Test method	Values
Specific gravity at 15 C	ASTM D 4052	0.83
Net calorific value, MJ/kg	ASTM D 4809	43.8
Flash point, ^{o}C	ASTM D 93	50
Fire point, ^{o}C	ASTM D 93	56
Pour point, ^{o}C	ASTM D 97	-6
Cloud point, ^{o}C	ASTM D 2500	-
Carbon residue, %	ASTM D 4530	0.1
Auto-ignition temperature, °C	ASTM E659	210-350
Kinematic viscosity at 40 ^{o}C, cSt	ASTM D 445	2.58
Cetane number	ASTM D 613	50
Moisture content, wt%	-	0.025
Boiling point, ^{o}C	ASTM D 86	344
(A/F ratio)$_s$, vol. %	-	14.6
Ultimate analysis		
Carbon, wt.%	ASTM D 3178	85.3
Hydrogen, wt.%	ASTM D 3178	13.19
Nitrogen, wt.%	ASTM D 3179	1.21
Sulphur, wt.%	ASTM D 3177	0.3
Oxygen, wt.%	ASTM E 385	Nil
Carbon/Hydrogen ratio	-	6.46

Table 2 Composition of biogas produced from Karanja de-oiled cake.

Gas constituents	Volume fraction, %	Density at 1 atm @ 15 ^{o}C, kg/m^3
CO_2	17.37	0.19800
O_2	1.5	0.21600
C_nH_{2n}	Nil	-
CO	Nil	-
H_2	1.4	0.00126
CH_4	73	0.20239
N_2	6.5	0.57500
H_2S	0.23	0.00735

Properties	**Biogas from Karanja cake**	**Biogas from cow dung**
Calorific value, MJ/kg	27.53	17.2
Density at 1 atm @ 15 °C, kg/m^3	1.2	1.24
Flame speed, m/s	25	21
Stoichiometric A/F, kg of air/kg of fuel	17.23	15.3
Flammability limits, vol% in air	7.5-14	7.5-11.7
Octane number	130	110
Auto-ignition temperature, °C	600-650	640-670
Energy content, kW/m^3	6.0-6.5	4.5-5.3
Fuel equivalent, L oil/m^3 biogas	0.6-0.65	0.42-0.5
Explosion limits, % in air	6-12	6-9
Critical pressure, bar	75-89	70-85
Critical temperature, °C	-82.5	-80.1
Boiling point, °C	-120 to -150	-130 to -162

Table 3 Biogas properties.

C. Experimental Setup

The experiment was conducted using a single cylinder, four stroke, air cooled DI diesel engine. The schematic of the experimental setup is shown in Figure 1 and the test engine specifications are given in Table 4. In the present investigation, the engine was used to operate in dual fuel mode with diesel as injected fuel and biogas as inducted fuel. For loading the engine, an electrical dynamometer (Make: Kirloskar, WHD10075, ACG) with a maximum brake power of 6 kW was coupled with the engine shaft. The electrical dynamometer was loaded by an electrical resistance type load bank. The engine speed was measured by a non-contact type speed sensor connected near the flywheel of the engine.The air flow into the engine was measured with a differential pressure sensor fitted in the air box. The differential pressure sensor gave a proportional voltage output by measuring the pressure difference before and after the orifice plate. To ensure steady flow of inducted air, a surge tank was used to damp out the pulsations produced by the engine. The exhaust gas temperature was measured with a K-type thermocouple fitted in the exhaust manifold. The fuel measuring system consisted of a vertical burette (30 cm³) fitted with two optical sensors, one at the higher end and other at the lower end of the burette. From this, time taken to consume the certain volume (20 cm³) of fuel was calculated.

An exhaust gas analyzer (AVL, 444) was used to measure the carbon monoxide (CO), carbon dioxide (CO2), nitric oxide (NO), unburned hydrocarbon (HC) in the engine exhaust. The gas analyzer measures emissions like HC, CO and CO2 based on the NDIR (Non-dispersive infrared) principle and the NO emission was measured with the help of electro-chemical sensor. The smoke density in the exhaust was measured with the help of a diesel smoke meter (AVL, 437C).

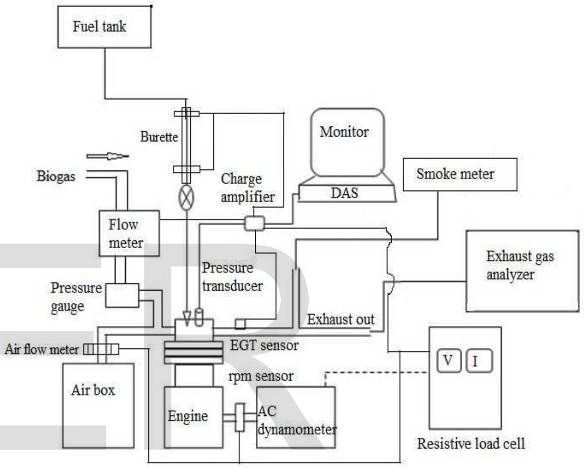

Figure 1 Schematic of the experimental setup

Table 4 Specifications of the test engine

Make/model	Kirloskar TAF 1
Engine type	Vertical, four stroke, single cylinder, air cooled, CI engine
Brake power, kW	4.4
Rated speed, rpm	1500
Number of cylinder	One
Cooling system	Air cooled
Air intake system	Naturally aspirated
Bore, mm	87.5
Stroke, mm	110
Displacement volume, cm^3	662
Burning clearance, mm	1.1-1.2
Compression ratio	17.5:1
Injection nozzle	MICO BOSCH, 3-hole nozzle
Nozzle opening pressure, bar	200
Standard Injection timing CA (bTDC)	23

D. Experimentation

The performance and emissions characteristics in the dual fuel operation were investigated by advancing the fuel injection timing. The injection timing was advanced by changing the thickness of the shims used in the fuel injection pump. The thickness of each shim is 0.3 mm and by removing one shim, the injection timing is advanced by 1.5°CA. In diesel operation, the injection timing was set at 23°CA bTDC . In dual fuel operation, the biogas flow rate was kept constant (0.9 kg/h) and the diesel injection timing was varied from 23-27.5°CA bTDC in a step of 1.5° CA. In both single a nd dual fuel operation, the engine was set to run at a constant speed of 1500 rpm and at an injection pressure of 200 bar with standard compression ratio of 17.5:1. In each operating module the engine was loaded up to 100% load in a step of 25%. During experiment the engine was first run with diesel and the results obtained were compared with the results that from dual fuel operation.

During the investigation, the mass of the pilot fuel consumption was regulated by the con-ventional governor controlled mechanism according to the variation of the load. The test conditions for this experiment are given in Table 5.

Table 5 Engine experimental test conditions.

Test fuel	Diesel, diesel + biogas
Engine speed, rpm	1500
Ambient air temperature, ^{o}C	23
Inducted biogas temperature, ^{o}C	20
Single fuel mode	Fuel: Diesel Diesel injection timing: 23^{o}CA
Dual fuel mode	Fuel: Diesel + biogas (0.9 kg/h) Diesel injection timing: 23, 24.5, 26, 27.5^{o}CA
Biogas induction pressure, bar	1.5
Biogas + air induction timing	35 CA bTDC
Diesel injection pressure, bar	200
Engine load variation, %	0, 25, 50, 75, 100

II. Result and discussion

A.Brake specific energy consumption (BSEC)

Figure 2 shows the BSEC for diesel operation and dual fuel operation according to the variation of brake mean effective pressure (BMEP), at different injection timing.

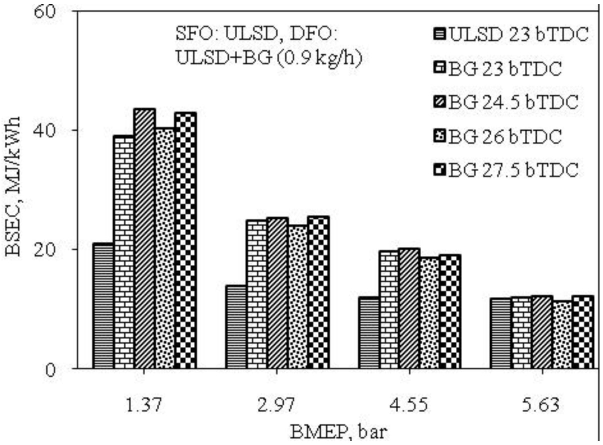

Figure 2 Variation of BSEC with BMEP.

It is noticed that, the BSEC for the dual fuel operation is higher than that of diesel opera-tion, which is due to the lower volumetric efficiency of dual fuel operation and lower en-ergy density to the unit mass of fuel [22]. The BSEC in the dual fuel operation has a large variation with pilot injection timing at low loads. However, the variation of BSEC with the injection timing is much less at medium and full loads. It is also observed that, at low loads advanced injection timing causes an increase in BSEC and contrarily at full loads ad-vanced injection timing reduces BSEC. At low load a minimum BSEC of 20.9 MJ/kWh and at full load a minimum BSEC of 11.7 MJ/kWh was achieved at an injection timing of 23oCA bTDC for diesel operation. In dual fuel operation, the minimum BSEC of 38.9 MJ/kWh was achieved at an injection timing of 24.5oCA bTDC at low load, whereas at full load the minimum BSEC of 11.3 MJ/kWh was achieved at an injection timing of 26oCA bTDC. It is believed that at full load condition, with high in-cylinder temperature, advanced pilot injection timing results in decreased BSEC because it allows for greater vaporization of the pilot fuel and better air-fuel mixing. The combination of these effects results in a greater engine power relative to later injection timing cases. At higher engine loads, however, it is considered that the in-cylinder temperature during the compression stroke increases, reducing the energy loss from fuel vaporization. Thus, the pilot injection fuel requires less time to obtain critical energy for auto-ignition.

The exhaust gas temperature obtained at different injection timings with BMEP were re-corded and depicted in Figure 3. It can be observed from the figure that, the exhaust gas temperature increases with increase in the BMEP. In diesel operations the maximum ex-haust gas temperature of 331.8 oC was obtained at BMEP of 5.6 bar. The exhaust gas tem-peratures for the dual fuel operation with advanced injection timing are increasing steeply compared to that of diesel operation. This may be due to the effect of advanced injection timing enhances combustion rate resulting in a high cylinder temperature and thus increase in exhaust gas temperature [23]. The dual fuel operation with the injection timing of 27.5 oCAbTDC exhibits the highest value of exhaust gas temperature of 333.3 oC at BMEP of 5.6 bar. The dual fuel operation with injection timing of 23 oCAbTDC exhibits a lower exhaust gas temperature in comparison to other injection timings. This decrease in the exhaust gas temperature is due to lower density of inducted biogas which decreases the local adiabatic flame temperature by absorbing the heat energy to auto ignite during combustion.

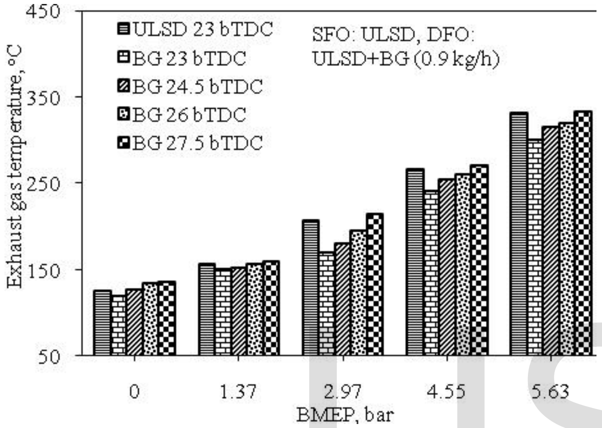

Figure 3 Variation of exhaust gas temperature with BMEP.

B. Emission analysis.

Figure 4 shows the of CO emissions for diesel and dual fuel operation at different injection timing with the variation of BMEP. In general the CO emission is due to the incomplete combustion of fuel. The CO emission is high at a lower BMEP due to poor mixture forma-tion, but as the engine load increases the BMEP also increases and there is a decrease in the CO emission. But at a maximum BMEP of 5.6 bar, the CO emission for diesel and dual fuel operation is in an increasing trend. This is due to the consumption of more pilot fuel at relatively high load and lower volumetric efficiency. In dual fuel operation, a reduction in the CO emission was observed with the advanced injection timing. This is due to increased oxidation process between carbon and oxygen molecules at relatively higher cylinder tem-perature [19,24]. Dual fuel operation with pilot injection timing of 26 oCAbTDC gives 17.3% lower CO emission than that of dual operation with injection timing of 23oCAbTDC at BMEP of 5.6 bar respectively.

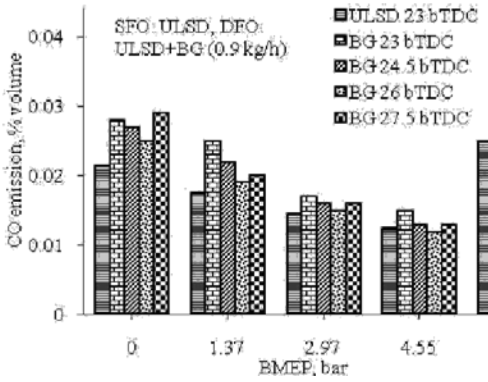

Figure 4 Variation of CO emissions with BMEP.

The influence of different BMEP and injection timing on HC emission is shown in Figure 5. The HC emission is due to the incomplete combustion of the fuel. It can be observed from the figure that, the HC emission is in a decreasing trend with the increase in the BMEP for both single and dual fuel operation. This higher HC emission at lower BMEP is due to the lean fuel-air mixture may survive to escape into the exhaust due to poor fuel distribution, large amount of excess air and low combustion temperature [25,26]. At higher BMEP the HC emission is observed to be lower compared to low BMEP. This is because at higher BMEP the increased combustion temperature results reduction in HC emission [24]. In dual fuel operation, the HC emission decreases with advancing the injection tim-ing. This may be due to the advancement in injection timing causes earlier start of combus-tion relative to the TDC, so the cylinder temperature becomes higher and there is a proper combustion of the compressed charge in the combustion chamber, and thus lowered HC emissions [27,28].

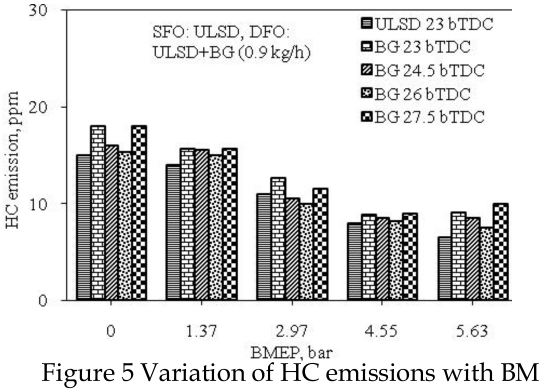

Figure 5 Variation of HC emissions with BMEP.

The variations of NO emission at different injection timing with BMEP for single and dual fuel operation is depicted Figure 6. The NO emission is highly dependent on the in-cylinder temperature, availability of oxygen and residence time for the reaction to take place [29,30]. It is observed that the concentration of NO emission is increasing with the increase in the BMEP for both single and dual fuel operation.The NO emission for diesel operation is higher than that of dual fuel operation. This is due to the faster burning of die-sel. In dual fuel operation, the biogas contains about 17% CO2 which suppresses the rapid combustion. The dual fuel operation with the advanced injection timing gives a gradual increase in the NO emission. This is due to higher combustion temperature at relatively advanced injection timing.

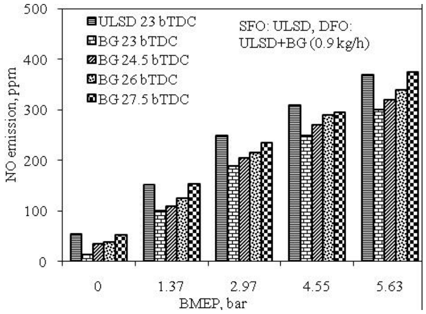

Figure 6 Variation of NO emissions with BMEP.

Figure 7 shows the variation of smoke density at different injection timing with BMEP. In general the smoke formation occurs due to extreme air deficiency [22]. It is observed that, the smoke density is increasing with the increase in BMEP. This is due to the increase in diesel consumption at relatively high BMEP, which contains aromatic compounds [30]. In the dual fuel operation, the lower smoke emission was observed with advanced injection timing.This is due to the higher combustion temperature during the combustion, and more time for the oxidation of the soot particles [28].

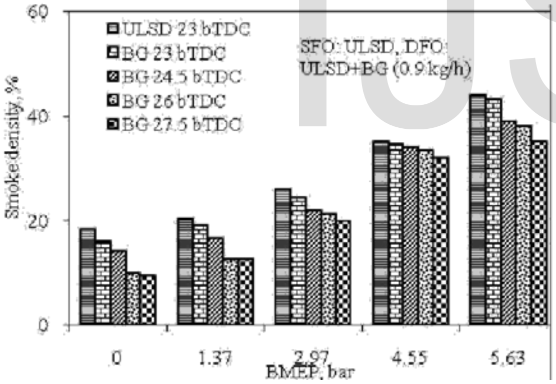

Figure 7 Variation of smoke density with BMEP.

III. Conclusion

The conclusions of the results obtained from the investigation are given as follows:

In the dual fuel operation, the advanced injection timing of 26 oCAbTDC gives a better performance and lower emission than that of other injection timings.

The BSEC for dual fuel operation at injection timing of 26 oCAbTDC was found to be higher by about 3.4% than that of diesel operation at BMEP of 5.6 bar respectively

Dual fuel operation with injection timing of 26 oCAbTDC gives 3.8% and 13% higher CO and HC emission than that of diesel operation at BMEP of 5.6 bar respectively.

The NO and smoke emission are lower by about 8.1% and 13.8% in the dual fuel opera-tion with injection timing of 26 oCAbTDC at a maximum BMEP of 5.6 bar respec-tively.

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