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Effects of oxy-acetylation on performance, combustion and emission characteristics of Botryococcus braunii microalgae biodiesel-fuelled CI engines

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ABSTRACT

Owing to the challenges associated with the application of synthetic/non-modified Botryococcus Braunii Microalgae Biodiesel (BBMB), its poor performance in CI engines has resulted in increased tendencies for non-commercialization of its fuel. The properties of a synthetic BBMB were controlled by acetylene addition. In this study, acetylene was induced with air at mass flow rates of 100, 150, 200 and 300 g/hr in order to monitor the combustion, emission and performance behaviour of a 4-stroke (Kirloskar AV1), 5.2 kW diesel engine with enhanced injection timing, in which the algal biodiesel was introduced as its main fuel. The obtained results compared favourably with those of a conventional dual-fuel CI engine in terms of combustion, emissions and performance. The brake thermal efficiency (BTE) of the acetylated biodiesel improved by 3, 4, 3.6 and 5% due to acetylene addition. NOx emissions were higher for the acetylated-biodiesel, whereas, the release of CO_2, HC, and CO were seen to decrease due to the addition of acetylene. Based on the results, the performance, combustion and gaseous emissions of the biodiesel obtained from Botryococcus braunii improved as a result of adding acetylene thus making it a suitable replacement for the conventional diesel fuel used in CI engines.

1. Introduction

The most predominant energy fuels available in the past few decades, are fossil fuels. When these fuels combust in CI-engines they release toxic substances such as dust, hydrocarbons, NOx, particulate matter, CO, soot, CO_2 and other gases which impose danger on human health and the environment [1]. With the growing world population and extensive utilisation of fossil fuels, there is need for an environmentally friendly alternative source of fuel that will lead to energy conservation and unlimited supply, thus boosting its sustainability [1,2]. In lieu of the ease with which they are produced, renewable clean-burning fuels are considered reliable substitutes for their conventional counterparts.

Several researches are focused on searching for alternative fuels that will be suitable for use in CI engines with the aim of improving the efficiency of the engine and minimizing exhaust emissions [2,3].

Amongst the alternative fuels, biodiesel from micro-algae is a promising and highly attractive fourth generation biofuel. Besides its availability in most parts of the world, it is eco-friendly and gives cleaner gas during combustion [1,4]. When used as fuel, microalgae-biodiesel can considerably reduce NOx emissions by about 45–70% and produces some particulate matter alongside smoke in compression ignition engines. Other properties include, reduction in CO_2 emissions, engine noise and vibration, with a substantial improvement in the brake-thermal efficiency of the engine [4,5].

Compression ignition engines are well-known to be compatible with some biodiesel fuels and their blends, which invariably improves performance and combustion properties when compared to diesel fuels [6]. CI engines operating on diesel fuels or their hybrids are usually injected into a charged mass of compressed air which is spontaneously ignited at high temperature before compression which helps to convert the fuel's heat energy into mechanical energy [7,8].

Microalgae can be used to produce different biofuels, which include

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bio-ethanol by fermentation, bio-methane produced by anaerobic digestion, liquid oil by thermal liquefaction and biodiesel and bio-hydrogen by photo-biological process [4]. Its biofuel appears to have a sustainable product-yield of 19,000–57,000 L/acre, which makes it a potential replacement for diesel from fossils [9]. Algae grows in aquatic environments with the help of sunlight, CO_2, inorganic constituents and H_2O to create biomass [10]. Botryococcus *braunii* microalgae, contains about 82% lipid-dry weight, which corresponds to a lipid product-yield of about 650 times above that of sunflower and colza plants whose productive capacities permit considerably high biodiesel yields [8,10,11]. Fig. 1. Shows a sample Botryococcus *braunii* micro algae. There are several ways of obtaining biodiesel from microalgae as illustrated in Table 1. They include chemical solvent method, biochemical/physicochemical extraction etc.

There are four main classes of microalgae, namely: Chrysophyceae, Bacillariophyceae, Chlorophyceae, and Cyanophyceaes; these species are not suitable for the production of biodiesel. However, the green algae taxonomic group which include the Botryococcus sp., *Dunaliella* sp. and *Chlorella* sp. are very ideal candidates for biodiesel production [12,13].

The performance of biodiesel in CI engines is dependent on the oil source [5–7]. Research has shown the potential of biodiesel as replacement for conventional diesel fuel, in terms of giving less emissions and greenhouse gases when used in CI engines. Furthermore, improved biodiesel properties can possibily be obtained by the addition of some special property-improvers in order to bring these emissions and other environmental degradation concerns to the nearest minimum [1,7].

Previous studies on the application of BBMB in CI Engines have been documented. The study by Tüccar et al. [10] is an experimental investigation carried out a four stroke-four-cylinder diesel engine, where the authors tested several blends of biodiesel and conventional diesel, such as B5, B10, B20 and B50 which consisted of 5:95%, 10:90%, 20:80% and 50:50% microalgae biodiesel: conventional diesel, as a means of compensating for the lower cetane number of the pristine microalgae biodiesel. Reduction in the engine power-output of about 6% was recorded for the unblended biodiesel (B100) compared to conventional diesel fuel. According to the authors, the reduction was ascribed to the low cetane number (poor fuel properties) of the microalgae biodiesel which subsequently gave rise to incomplete combustion. However, a drop in CO emissions was noted for the fuels. Oni et al., [14] investigated the emission and performance characteristics of blended Jathropha Curcas L. biodiesel with biodiesel from *Spirulina Platensis* microalgae in a Kirloskar VI diesel engine. The results showed an increase in brake-specific fuel consumption (BSFC) compared to those of standard diesel fuels. The emission results indicated that the blends reduced the HC, CO, and CO_2 emissions with an increase in NOx emission. Haik et al. [15] used a raw algae biodiesel in an indirect injection diesel engine with single cylinder. The effect of heat release rate, engine load, compression ratio, engine speed and injection timing were studied. The result showed that 10% methanol in the algae biodiesel fuel, gave better performance. With delayed injection timing, there was reduction in combustion noise. Saddam Al-lwayzy and Talal Yusaf [16] adopted microalgae biodiesel from *Chlorella protothecoides*, blended with diesel fuels in a tractor engine. The brake thermal efficiency, engine torque and brake power, were closer to those of the diesel fuel with slight variation (i.e., 2% reduction in torque and 1% reduction in engine power). Also, the emission properties of CO and CO_2 were found to be lower than those of standard diesel fuel with resultant higher NOx emissions. Hariram and Kumar [17] conducted an experiment using microalgae biodiesel blended with conventional diesel fuel in a single cylinder direct injection diesel engine; the resulting BTE and BSFC showed appreciable improvement over those of the conventional diesel fuel. The HC, smoke, CO and particulate matter from the exhaust decreased, while they recorded an increase in NOx emissions. Yadav et al., [2] carried out a physicochemical characterization of the exhaust gas emissions of algal biodiesel blended with conventional diesel fuel, which they compared with those from unblended diesel fuel in a VCR single-cylinder diesel engine operating on different loads. Of all the blends, the AB30 blend gave minimal emissions with a reduction in CO and HC emissions. However, the increase in NOx emissions were in the range of 25–30% due to the presence of unsaturated moieties. Reddy et al. [18] conducted an experiment on the suitability of *Schizochytrium* microalgae biodiesel as a substitute for conventional diesel fuel. The results show that the resulting BTEs were appreciably close to those measured for conventional diesel fuels at full load condition. There was a reduction in CO_2 and HC emissions compared to those of the standard diesel fuel whereas, higher NOx emissions were recorded. Engine tests for three fuel-blends were carried out by Tüccar et al. [19] in order to evaluate the effect of butanol addition in microalgae biodiesel + conventional diesel mix; the blends contained different proportions of a conventional diesel fuel, butanol and a fixed quantity (20%) of microalgae biodiesel. The experiments were also conducted on a four stroke-four-cylinder diesel engine. Engine speed in the range of 1200–2800 rpm was adopted at constant load condition. The net biodiesel used had a cetane number of 48.3, density of 886 kg/m^3 and viscosity of 4.47 mm^2/s. The engine power and torque outputs of the compared fuels, were slightly different owing to the addition of butanol, these they claimed may be associated with the lower heating value (LHV) of the blended fuel and fixed injection duration of the engine. The resulting HC and CO emissions decreased by 28 and 22%, respectively, as a result of the availability of more oxygen for improved combustion. However, the NOx emissions were seen to increase by 13% for the blended fuels, which is due to the high combustion temperature caused by the excess unreacted oxygen in biodiesel. Joshi and Thipse [20] conducted an experiment at an engine speed of 1500 rpm on a four stroke, single cylinder, direct injection, naturally aspirated diesel engine with compression ratio of 18 at several load conditions, so as to evaluate the combustion, performance and emission characteristics of algae biodiesel of 5, 10, 20 and 30% composition, compared to those of a conventional diesel–fuel. There was 5% decrease in the BTE, 7% increase in the brake specific fuel consumption and 3% increase in the exhaust gas temperature for the algae biofuel blends when compared to

Fig. 1. Botryococcus *braunii* microalgae.

Table 1
Biodiesel from microalgae lipids.

Extraction techniques	Solvent used/technique	Yield (g lipid/g dry weight)	Microalgae spp.	Reference
Chemical solvents	Chloroform-methanol	63%	–	[6]
	Hexane	55%	*Chlorella protothecoides*	[8]
Supercritical carbon dioxide extraction	Carbon dioxide extraction	26%	*Nannocloropsis* sp.	[10]
		30.8%	*Chlorococcum* sp.	[10]
		28.6%	*Botryococcus* sp.	[11]
Physicochemical extraction	Microwave	28.6%	*Botryococcus* sp.	[9]
Biochemical extraction	Cellulase hydrolysis pretreatment	54%	*Chlorella* sp.	[10]
Direct (in situ) transesterification	Acetyl chloride (CH_3COCl) + hexane	56%	–	[12]

conventional diesel. Islam et al. [21] tested *Crypthecodinium cohnii*-microalgae biofuel-blends in a 100 kW Peugeot 308 2.0 HDi four-cylinder, turbo-charged diesel engine with a torque of 320 Nm. Microalgae-diesel fuel blends, tagged, B10, B20 and B50 were tested. The calorific values of the blended biodiesel fuels were 10% lesser than that of the conventional diesel fuel, however, higher densities (7.8% higher) and viscosities (47.8% higher) were recorded for the microalgae blended fuels. All experiments were performed at a constant speed of 2000 rpm for varying engine loads. In addition, the microalgae biodiesel gave longer ignition delay and lower cetane number. Although, no significant differences were observed for the peak cylinder pressure of the microalgae biodiesel blended with conventional diesel, however, at 25% engine load, the cylinder peak pressure of the ordinary diesel fuel, rose 8% higher than those of the blended biodiesels, whereas, at less than 25% engine load, the reverse was the case. However, the pressure increase was found to be associated with long ignition delay. Rinaldini et al. [22] conducted an experiment on microalgae biodiesel used in a Lombardini 4-cylinder, 4-stroke naturally aspirated diesel engine operating on diesel fuel and a B20 blend of transesterified microalgae oil from Chlorella biodiesel from microalgae oil. The emission and performance characteristics were measured at full load condition. The B20 blend gave higher NOx emissions and reduction in soot/particulates. For the exhaust emissions, there was 30% reduction of soot at high load, slight reduction of 5–7% torque at high speed and 20% increase in NOx emission with 10% increase in CO_2 emissions at full load condition. There were slight reductions of O_2 for the B20 fuel at full load condition. Satputaley et al. [11] carried out an experiment on a four stroke, single cylinder, air-cooled diesel engine. The tests were carried out at varying loads with a maximum speed of 1500 rpm. Initially, the engine was run on conventional diesel fuel and algae biofuel. The results showed that the BTE of the diesel fuel was higher than that of the algae biodiesel. The engine power was lower when fuelled with algae biodiesel relative to that of the diesel fuel due to the lower calorific value of the biofuel as well as its high viscosity and density. The exhaust emissions, were lower in terms of CO with 50% HC emission-reduction compared to that of the diesel fuel. The NOx emission of the algae biofuel was higher, however, there was reduction in smoke emission for the biofuel relative to the diesel fuel at full load condition. Ahmed et al. [12] selected Spirogyra, Cladophora and Gracilaria microalgae species for the production of microalgae biodiesel which was used as fuel in an ISUZU 4FB1, water-cooled, four-stroke engine; the microalgae fuels were also blended with conventional diesel–fuel owing to the poor properties (high viscosity and density) of the microalgae fuels. The operating speed was in the range of 800–3600 rpm with an adjustment of 50% throttle setting for the engine performance/emissions tests. Based on the results, the recorded break specific fuel consumption (BSFC) increased with an increase in the percentage of the biodiesel blends; although, the microalgae biodiesel blends gave lower calorific values compared to those of the conventional diesel–fuel. Higher brake power outputs were recorded for the biodiesel-conventional diesel blended fuels which was seen to be slightly higher than that of standard diesel fuel. The increase in brake power of the biodiesel + standard diesel blend was found to be as a result of the improved combustion efficiency of the microalgae biodiesel caused by blending. At 1600 rpm, the maximum brake power for the conventional diesel fuel and the best biodiesel blended-fuel (B10) are 10.3 kW and 11.2 KW, respectively. For increased biodiesel contents in the fuel-blends, there was a corresponding reduction in CO emission and NOx with an optimum emission of about 40.4% compared to that of the conventional diesel–fuel. According to the authors, for lower biodiesel compositions in the fuel blends, the engine performance of the engine was not affected, whereas, the situation was worse for higher biodiesel compositions.

Considering previous investigations on the use of synthetic/non-modified (BBMB), problems associated with the fuel's quality have led to a dearth in its continuous use/commercialization as fuel for CI engines, this then served as a motivation for this study.

Based on the underscored related works on the subject, BBMB is a fuel that has high oxidative potential which makes it unsuitable for CI engines owing to its high knocking potential. Also, BBMB gives low BTEs which can result in engine malfunctions [16]. Its poor atomization [8] results from the high viscosity of the fuel when in contact with air, hence, the need for the inclusion of suitable additives to improve the degree of atomization of the fuel. There is also the problem of low heat release rate associated with BBMB owing to its poor peak pressure [13]. Other challenges include, long ignition delay and high emissions [1] all of which led to the need to select a suitable additive such as acetylene which despite helping to improve the atomization tendencies of the fuel, also helped to modify the properties of the fuels (BBMB) such that they release less emissions.

Acetylene (C_2H_2) is one of the several additives that can be used in blending biofuels for application in CI engines. It is a colourless/odourless gas [23–25] with low ignition energy [26] high flamability [27] high flame speed and fast energy release rate when used as fuel in compression ignition engines [28,29]. In stoichiometric quantities, acetylene can cause an engine to approach a thermodynamically stable/ideal cycle. When its self-ignition heat generation is high, higher compression ratios may become evident. Other problems associated with the use of acetylene only, as additive, in biofuels include: an increase in quenching distance, which is associated with a decrease in temperature thus lowering the combustion and HRR [30]. The characteristics of the acetylene used in this study are as illustrated in Table 2. Different proportions of the acetylene were adopted in order to ascertain the best fuel-composition with excellent performance, good combustion properties and, minimal emissions. Due to varied flammability limits,

Table 2
Physical and combustion properties of several fuels.

Characteristics	C_2H_2	Hydrogen (H_2)
Flammable limits (vol.%)	3–80	4–74.5
Ignition energy(mJ)	0.020	0.02
Auto Ignition temperature (K)	305	572
Lower calorific value (kJ/kg)	48,230	120,000
Stoichiometric air fuel ratio(kg/kg)	13.3	34.3
Flame speed(m/s)	1.5	
Density at 1 atm and 20 °C	1.091	0.08
Adiabatic flame temperature(K)	26,000	
Flammability limits (equivalent ratio)	0.3–9.6	0.1–6.9
Maximum deflagration speed (m/sec)	1.5	3.5
Low Heating value of Stoichiometric mixture (kJ/kg)	3396	3399

lower ignition energy, short quenching distance and high flame speed may result in untimely/delayed ignition which causes engine-knock; this is a common scenario with acetylene-fuelled engines. Also, the results of several researches clearly show that micro algae biodiesel possesses low engine performance due to fuel quality and higher NOx emission. To overcome these drawbacks, there is need to introduce an additive that will appreciably increase the brake thermal efficiency and further reduces the emissions, specifically the NOx emission in the CI engine, hence the introduction of acetylene. Several blends of micro algae biodiesel and acetylene were tested in a CI engine to determine the best blend for optimum engine performance, good combustion and reduced emissions, especially with respect to NOx gases.

In addition, acetylene is known to give low BTEs if not well-moderated, hence, the need to optimize the acetylene composition which must be mixed with the right amount of air for enhanced combustion. Thus, the amount of acetylene added as additive to the fuel was kept constant per batch operation (100 g/h, 150 g/h etc.), so as to improve the properties of the BBMB-fuel, towards achieving low emissions, however, despite its merit, one major challenge still associated with acetylene addition to BBMB/biofuels if not well-moderated, is the resulting low BTEs caused by insufficient mixing of acetylene and biofuel during combustion. Hence, in order to overcome the aforementioned challenges, atomization of acetylene was done by infusing it with air at varying flow rates, this is all aimed at improving the microalgae biodiesel properties when acetylene, air and BBMB come in contact in the combustion engine. Ashok et al. [25] discussed the comparative performance of two fuels; acetylene-only and acetylene-karanja biodiesel, in an air-cooled, single cylinder 4- stroke 5.2 kW power engine whose motor speed was fixed at 1500 rpm for a compression ratio of 17.5:1. The blended karanja biodiesel reduced the thermal efficiency of the break system whereas, an increase in the engine load decreased the specific energy consumption of the brake. Balasubramanian and Krishnan [31] studied the effect of acetylene-air mix in safflower biodiesel (SME) as fuel in CI engine. When the SME was used in place of conventional diesel, it resulted in inferior combustion caused by high density and viscosity of the biofuel. The acetylene was inducted with air-intake at various mass shares and the resulting gas was mixed with SME and conventional diesel fuel. The experiment was carried out at 50 and 100% loads and acetylene mass-shares until the engine approached its knock-limit. The air-induced acetylene improved the BTE of SME and diesel fuel by 6.6 and 14.3% at 100% load; they also observed that at 50% load, there was no significant improvement in the engine load when the quantity of acetylene was increased. The modified SME fuel gave higher NOx emissions compared to conventional diesel fuel at 50% and 100% load conditions. There were also low CO_2 and HC emissions caused by the ai-acetylene-SME mix. Sasikumar and Sankaranarayanan [32] investigated the emission and performance properties of biodiesel mixed with acetylene in a 4-stroke, single cylinder DI engine on dual fuel mode. They recorded about 3.52% reduction in the engine's BTE. The recorded NOx emissions also reduced by 15.90%, with an increase in HC (13.92%) and CO (12.78%) emissions when compared with those measured for conventional diesel fuel. Sonachalam et al. [3] conducted an investigation on the intake manifold of an engine with a close examination of its combustion, emission and performance characteristics at varying acetylene flow rates. The BTE of the engine was seen to increase by 3.7% at a flow rate of 4 LMP of acetylene injection in a RCCI combustion-mode, while there was a decrease of 7.6, 13.4% and 28.7% NOx, HC and CO emissions respectively as compared to those of conventional diesel fuel.

Since none of the related studies/literature hitherto, happens to have focused on blending BBMB with acetylene and air of varying compositions as a means of modifying the fuel's properties, therefore, the aim of this study is to investigate the effect of blending acetylene with air and BBMB for use in CI engines. In addition, due to the fact that oxyacetylene has a higher flammability relative to acetylene, as a way of improving its combustion properties, the acetylene-BBMB mix was oxidized with air at varying flow rates in order to enhance its combustion potential towards ensuring high engine performance and low emissions.

2. Materials and method

2.1. Method

Transesterification was the method adopted in producing BBMB from microalgae. For the microalgae biodiesel oil extraction using transesterification method, the chemicals (CH_2OH, n–C_6H_6, H_2SO_4, NaCl) all produced by (Sigma Aldrich Company, St.-Louis USA). *Botryococcus braunii* microalgae were obtained from Ota, Covenant University farm, Ogun State, Nigeria. The Microalgae were sundried for 72 h to allow water in the biomass to evaporate. The sundried microalgae were pulverised to powder and sieved through a 75-μm sieve to remove microalgae of larger sizes. 93% of the oil extracted from *Botryococcus braunii* microalgae was achieved by solvent extraction using the hexane (the properties of the crude microalgae oil are contained in Table A.1 in the supplementary file). Primarily, the oil was squeezed out by the aid of a mechanical press; the remaining microalgae were then mixed with hexane, after which, they were sieved and cleaned. After the extraction process, the oil was refined with NaOH and mixed with CH_2OH. The extract contained BBMB mixed with some glycerol. Glycerol removal was carried out by refining the obtained mix to produce the desired microalgae biodiesel (Figs. 2). The product/biodiesel was then stored for further analysis. Table 3 shows the equipment required for determining the properties of the microalgae biodiesel oil.

2.2. Oxy-acetylation of acetylene

It is necessary to note that several trial compositions of acetylene-air mixture were initially experimented in order to determine the best acetylene-air composition for use as additive. However, it was observed that for all trial runs, the ratio 2:1 (air: acetylene) was found to be the best air: acetylene composition for every dual mixture tested. In the experimental runs, since the whole idea was to keep the quantity of acetylene constant, several varying ratios of air to acetylene of fixed composition, in the order of 1:1, 2:1, 3:1, 4:1 and 5:1 were adopted using air-acetylene flow rates of 50–500 g/h (see supplementary file: Table A.2 in terms of engines performance). Based on the results obtained, flame tests were carried out at different air flow rates and it was observed that the fuels with the best flame properties were majorly those having air: acetylene ratio of 2:1 for the 100–300 g/h air-acetylene mix, whereas, others gave poor flame properties.

It is also important to note here that, the amount of acetylene added as additive to the fuel was kept constant per batch operation (100 g/h, 150 g/h etc.), owing to the fact that some studies have reported the positive effect of acetylene in fuels [34-36] i.e., it improves the properties of the fuels such that they release less emissions, but one major challenge still associated with acetylene addition to fuels, is the low BTEs of fuels caused by the presence of acetylene which in turn results in insufficient mixing of the acetylene-biofuel mixture during combustion. Hence, in order to overcome the aforementioned challenge, the authors decided to atomize the acetylene by infusing it with air at varying flow rates, all aimed at improving the microalgae biodiesel properties when the components (acetylene + air + BBMB) come in contact in the combustion engine.

Note: Several trial compositions of acetylene-air mixture were initially experimented in order to determine the best acetylene-air composition for use as additive. However, it was observed that for all trial runs, the ratio 2:1 (air: acetylene) was found to be the best air: acetylene composition for every dual mixture tested. In the experimental runs, since the whole idea was to keep the quantity of acetylene constant, several varying ratios of air to acetylene (fixed) of 1:1, 2:1, 3:1, 4:1 and 5:1 were adopted using air-acetylene flow rates of 50–500 g/h.

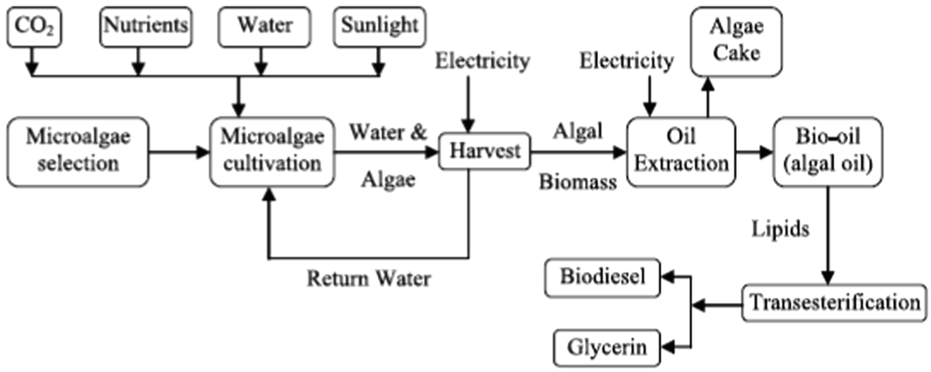

Fig. 2a. Flowsheet of BBMB production.

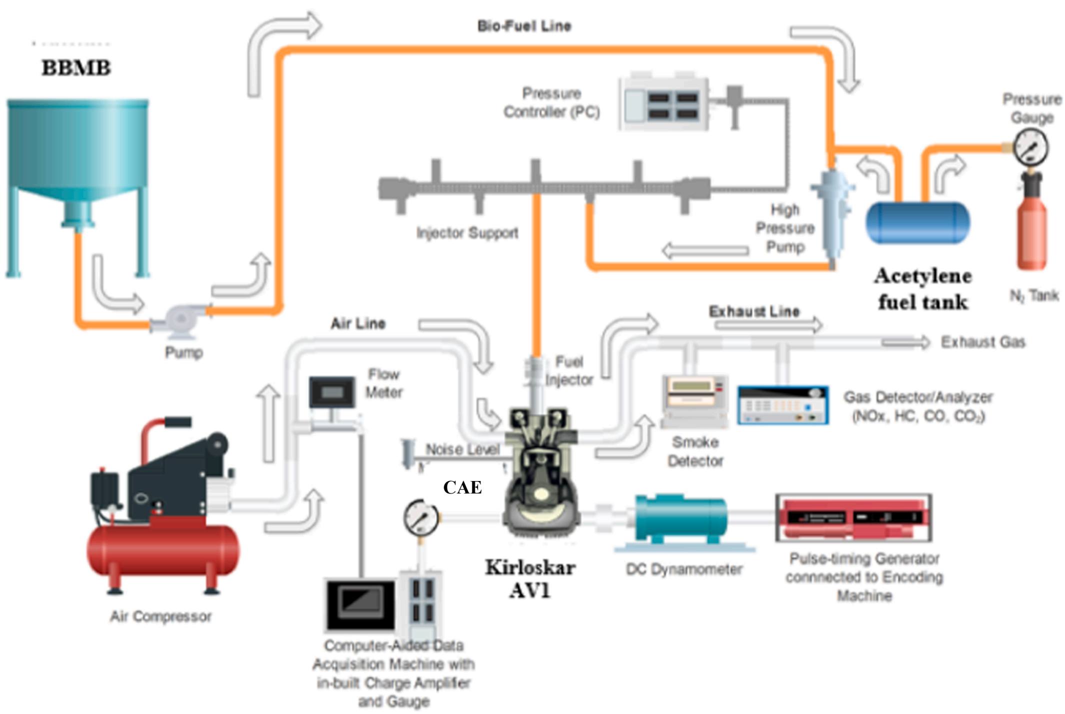

Fig. 2b. Engine test equipment for Kirloskar AV1which shows the most important elements.

Table 3
Equipment for determining the properties of the microalgae biodiesel oil.

Item	Equipment	Manufacturer	Test method
K. Viscosity	SVM 300	Aanton par, United Kingdom	ASTM D445
Density	SVM 300	Aanton par, United Kingdom	ASTM D4052
Flash point	Cleveland open cup NDJ-3742	Shanghai, PR China	ASTM D93
Pour and cloud point	PCP NTE 450	Norma lab., France	ASTM D2500
Cold filter plug point	CFPP- automatic NTL 4500	Norma lab., France	ASTM D6371
Oxidation stability	856- Rancimat	Metrohm, Swiss	EN ISO 14,112
V.I	SVM 300	Aanton par, United Kingdom	N/A

Based on the results obtained, flame tests were carried out at different air flow rates and it was observed that the fuels with the best flame properties were majorly those having air: acetylene ratio of 2:1 for the 100–300 g/h air-acetylene mix, whereas, others gave poor flame properties. The ASTM E594-96 standard procedure was used in determining the flame properties of the different air-acetylene blends.

2.3. Engine-test for the biofuels

The engine (Kirloskar AV1) was adjusted to work on dual fuel method (engine specification and test equipment are shown in Table 5 and Fig. 2) by introducing acetylene at varied flow rates of 100. 150, 200 and 300 g/h respectively in the intake pipe, containing the produced biodiesel from *Botryococcus braunii* microalgae in order to prevent excess heat in the intake port. Thus, A1 for Microalgae biodiesel/acetylene at 100 g/h, A2 (Microalgae biodiesel/acetylene at 150 g/h), A3 (Microalgae biodiesel/acetylene at 200 g/h) and A4 (Microalgae biodiesel/acetylene at 300 g/h); the properties of the blended fuels are as shown in a later section. Acetylene gas was stored in a pressure cylinder of fifteen bar and reduced by a regulator to one bar. A valve controlling the acetylene flowrate, while flow measurements were taken by the gas flowmeter attached to the cylinder. Acetylene was passed through the injector (a non-return valve) and flame trap. The airflow rate was determined through the pressure drop across the orifice of the air chamber using a sensor. Burettes calibrated at 0.1 cc accuracy were used to determine the fuel consumption. Furthermore, the exhaust gas temperature was calculated using a thermocouple joined to a thermometer. Lennon pressure transducer (NDJ193L) was used to determine the cylinder pressure. The crank position was calculated by using an encoder and a sensor attached on the flywheel. All emissions, CO, CO_2, NO_X, Unburnt hydrocarbons were measured using HM5000 Handheld Gas Analyser. Table 4 gives details on the range, accuracy and uncertainty of the equipment used for the investigation.

Furthermore, the emission characteristics of the exhaust gases (g/kwh) were determined using correlations. The emission concentrations from ppm to g/kWh for the NOx, CO, and HC were determined using the correlations (equations 1–3) established by Ağbulut et al. [37]; the results are as presented in Tables A.3 – A.5 of the Appendix of the Supplementary file.

$$CO(\frac{g}{kWh}) = 3.591 \times 10^{-3} \times CO(ppm) \quad (1)$$

$$HC(\frac{g}{kWh}) = 2.002 \times 10^{-3} \times HC(ppm) \quad (2)$$

$$NO_X(\frac{g}{kWh}) = 6.636 \times 10^{-3} \times NO_X(ppm) \quad (3)$$

3. Results and discussion

Tables 6 and 7 show the results of the crude *Botryococcus braunii* microalgae oil properties, properties of conventional diesel fuels and microalgae biodiesel. Fig. 3 is an illustration of the gas chromatogram of the BBMB. The density, flash point and viscosity and cetane number of the conventional diesel fuel is lower than that of the BBMB, this is attributed due to the presence of oxygen in the biodiesel fuels this is in line with the findings of [7,28]. However, the calorific value of the diesel fuels is higher than the biodiesel fuels.

*Methyl undecanoate (11:0); Methyl laurate (12:0); Methyl tridecanoate (13:0); Methyl myristate (14:0); Methyl pentadecanoate (15:0); Methyl palmitate (16:0); Methyl palmitoleate (16:1); Methyl heptadecanoate (17:0); Methyl stearate (18:0); Methyl oleate (18:1); Methyl linoleate (18:2); Methyl linolenate (18:3)

The results of the raw BBMB (without acetylene and air), are as illustrated in Fig. 3. It shows the composition of the BBMB produced via transesterification. Again, considering the carbon numbers of the BBMB which span from C11-C18, actually confirms that the BBMB consists mainly of the carbon chain lengths that depicts biodiesel (i.e., methyl laurate, methyl tridecanoate, methyl myristate, methyl pentadecanoate, methyl palmitate, methyl palmitoleate, methyl heptadecanoate, methyl stearate, methyl oleate, methyl linoleate and methyl linolenate.

Fig. 4 illustrates the variation of combustion pressure versus crank angle at full load for the diesel and microalgae biodiesel – acetylene

Table 4
Range and accuracy of various instruments with their uncertainties.

Instrument	Range	Accuracy	Uncertainty (%)	Techniques for measurement
Crank angle encoder (Legion Brothers)	–	±1	1.0	Magnetic type
Burette fuel measurement	1–30 cc	±0.20*cc*	1.5	Volumetric measurement
NOx (AVL 444)	0–5000 ppm	±50*ppm*	±0.2	Electrochemical measurement
Load Indicator	0.25–1 kW	0.1*kg*	0.20	Strain gauge type load cell
Smoke meter (AVL 437C)	0 –100%	±1%	1	Opacimeter
Temperature indicator	0 –900	±1°C	0.15	thermometer
Speed sensor	0.0–10000 rpm	±10*rpm*	±1.0	Magnetic pickup type
Pressure transducer (Type NDJ193L, Lenon Instruments, Netherland)	0 –110*bar*	±1*bar*	0.15	Piezoelectric sensor
CO_2 (AVL 444)	0 –20%	±0.03%	±0.15	NDIR principle
HC (AVL 444)		±20*ppm*	±0.2	NDIR principle
CO (AVL 444)	0–10%	±0.02%	±0.2	NDIR principle
Time	–	±1*s*	±0.20	Stopwatch
Exhaust gas temperature				
Manometer		±1.0*mm*	±1.0	Column of liquid balancing

Table 5
Engine specification.

Engine Type	Kirloskar AV1
Rated output	5.2 kW at 1500 revolutions per minutes
Engine	Single cylinder, direct injection diesel engine
Injection Pressure/timing	200 bars/23°before TDC
Dynamometer	Eddy current
Nozzle type	Multi hole
Resolution crank	1°crank angle
Bore/stroke/compression	Ratio 87.5/110 mm/17.5:1
Piston type	Bowl-in-piston
EGT	RTD Thermocouple
Angle sensor	360° encoder with resolution of 1°
Fuel flow measurement	Burette with Digital Stopwatch
Capacity/No. of holes	661 cm^3/3

Table 6
Crude Botryococcus braunii microalgae oil properties.

Properties	Units	ASTM Test	Crude algae
Density.	Kg/m^3	D0445	879
Flash point	°C	D93–2A	148
Viscosity at 40	mm^2/s	D445–4E02	21
Acid value	mgKOH/g-oil	D664	0.11
Sulphur content	%	D129	0.00
Pour point	°C	D97–05A	2
Ash content	%	D0428-03	0.01
Dynamic Viscosity	mPaS	D445	36.4
Cetane number	–	D613-84	40.9
Residue of carbon	%	D0524	0.01
Calorific value	mJ/kg	D240	42.07
Cloud point	°C	D2500 –05	6

Table 7
Properties of Diesel fuels and Botryococcus braunii microalgae biodiesel

Properties	Unit	ASTM Test	Diesel fuel	Algae oil biodiesel
Density	Kg/m^3	D0445	866	892
Flash point	°C	D93–2A	46	189
Kinematic Viscosity at 40	mm^2/s	D445–4E02	4.5	62
Acid value	mgKOH/g-oil	D664	0.062	31
Pour point	°C	D97–05A	−3	3.11
Dynamic Viscosity	mPaS	D445	2.01	4.68
Cetane number	–	D613-84	41	52
Residue of carbon	%	D0524	–	0.02
Calorific value	mJ/kg	D240	42,200	36,765
Cloud point	°C	D2500 –05	−1	5.07
Fire point	°C	D93	59	205

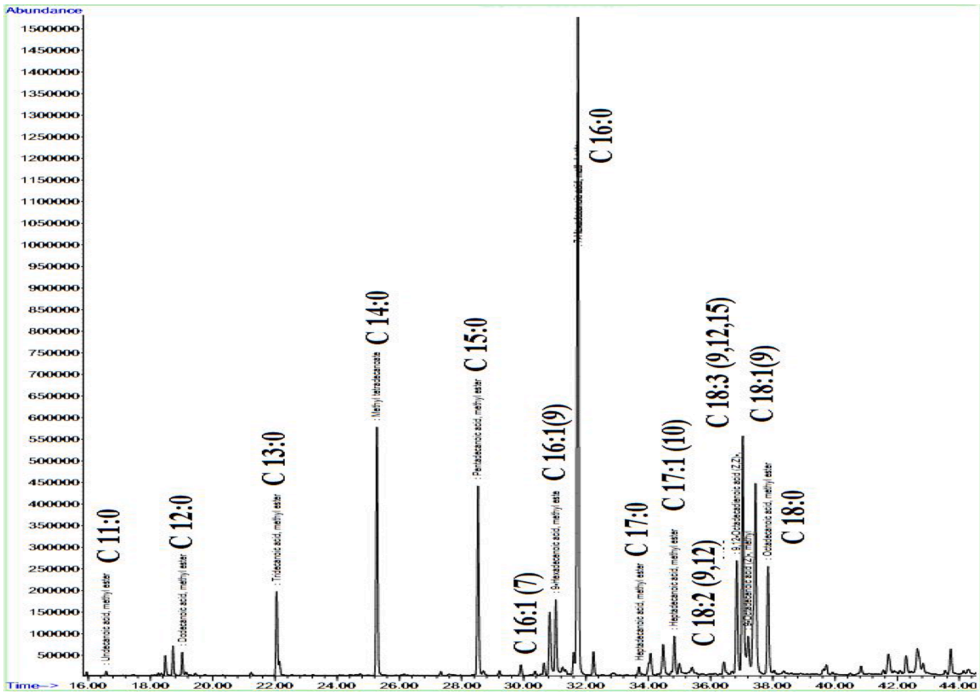

Fig. 3. Gas chromatogram of the raw BBMB.

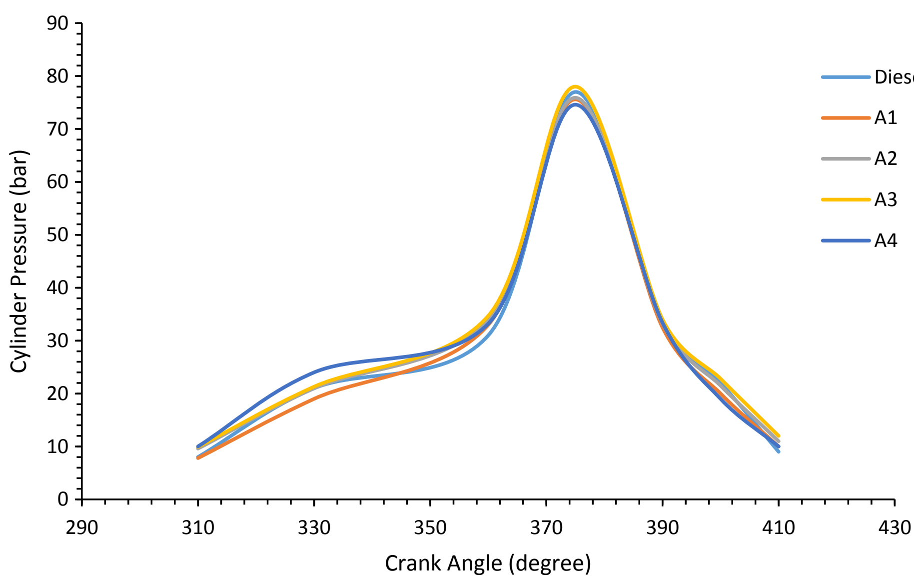

Fig. 4. Cylinder Pressure with Crank Angle at Constant Load.

blend at different flow rates. In-cylinder pressure can be influenced by the degree of prepared fuel throughout the delay interval for the pre-mixed combustion [24]. Microalgae–acetylene biodiesel blend has wide-ranging flammability, and involves low ignition energy since the engine can work in lean mode at very high specific heat ratios which may result in higher thermal efficiency. For full load diesel operation, the maximum allowable cylinder pressure is 77 bar, and for algae biodiesel – acetylene, the values are 75.6, 75.9, 78.0 and 74.6 bar. Variations in flow rate for the Microalgae biodiesel – acetylene mix include 100, 150, 200 and 300 g/h respectively. Peak pressure largely depends on the rate of combustion at the preliminary phases which is affected by the intake of the fuel components in the unrestrained heat release stage. Reduction in peak pressures for biofuel samples A1, A2 and A4 were obtained with the exception of sample A3 whose cylinder pressure increased. The low peak pressures of A1, A2 and A4 are due to their low heat release rates beyond 330° as compared to samples A3 and that of the conventional biodiesel; this corroborates the findings of [38]. Considering Fig. 5, it can be seen that above a crank angle of 330°, i.e., 330, 360, 390, 420 and 450° the corresponding heat release rates for sample A1 = 22, 62, 20, 10 and 2.4 J/°CA respectively, for sample A2 = 23, 61, 21.5, 11 and 3 J/°CA respectively; for A3 = 2, 64, 22.8, 12 and 3.3 respectively; while for sample A4, the corresponding heat release rates = 23, 63, 23, 10 and 3.1 respectively. Now based on the reported heat release rates, it is obvious that beyond a crank angle of 330°, (i.e., 330–450°), the heat release rate of sample A3 was highest from that point onwards compared to those of other samples and this in turn caused the cylinder to do more work, hence, there is an increase in cylinder pressure, which is in line with the findings of [38]. These also confirm why the cylinder pressures of all the

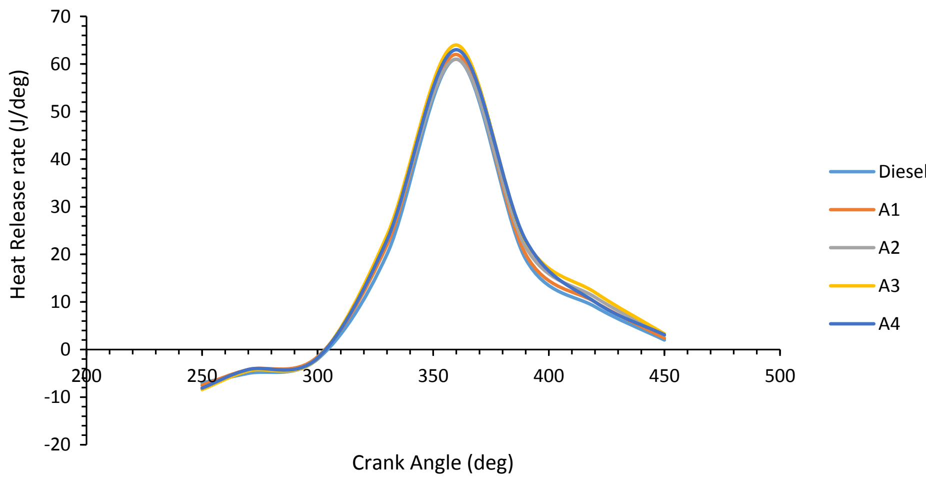

Fig. 5. Variation of Heat Release Rate with Crank Angle at Constant Load.

samples are in the following ascending order: A4 (74.6 bar), A1 (75.6 bar), A2 (75.9 bar), Diesel (77) and A3 (78 bar), respectively.

From Fig. 4, biofuel samples A1-4 combustion occurs earlier for the biofuel as compared to the diesel fuel due to the high cetane status/ number of the fuel for those biofuel samples, which in turn decrease the delay period of the fuel, thus reducing the risks associated pre-mixed combustion. The enhanced calorific value and wide flammability range result in improved combustion. In addition, better commingling of acetylene and air during the delay leads to higher peak pressures [26]. Also, the occurrence of peak pressure with acetylene addition when compared to the biodiesel, is due to fast combustion of acetylene [3]. The cylinder peak pressure is highest for A3 at crank angle of 375° and cylinder pressure of 78 bar. The high pressure is due to high Exhaust Gauge Temperature (EGT) and uncontrolled combustion, and the rate at which heat is released during the pre-mixed combustion is accountable for the cylinder peak pressure [24].

The heat released from the combustion chamber obeys the first law of thermodynamics for closed systems. Fig. 5 illustrates the rate at which heat is released for diesel operation and acetylene operated dual fuel engine inducted with algae biodiesel at different crank angles and flowrates. The maximum heat released at full load for diesel operation is 61 J/deg and for acetylene induction with microalgae biodiesel, the heat-release rates for A1, A2, A3 and A4 are 62, 61, 64 and 63 J/deg. respectively. The differences in crank angles of samples (A1-A4) range from (1–3 J/deg.). These differences were indeed noticeable based on the level of accuracy (±1)and uncertainty measurement limits (1%) of the crank angle encoder (Table 1) which was employed in this research i. e., it has the ability to take measurements within these specifications, this agrees with the results of [11]. Also, monitoring of these variations was necessary owing to the fluctuations observed for the different samples, with sample A3 giving the highest crank angle, whereas, sample A1 gave the best results in terms of BTE, HRR and emissions with a medium crank angle of 62 J/°. Hence, it is necessary to maintain the crank angle of the engine at 62 J/° if the best results are desired.

The heat rate chart can be further differentiated into four separate phases namely; pre-mixed combustion, ignition delay, mixed controlled combustion and the late combustion phases. The rate at which heat is released for acetylene injection demonstrates distinct explosive properties of pre-mixed type combustible fuel accompanied by a brief second phase dip in heating rate which rapidly increases during the third phase of combustion of the gas [27]. From Fig. 5, the net heat release rate is high for biofuel sample A3; at 360 °CA, biodiesel fuels experience a speedy pre-mixed combustion accompanied by diffusion combustion, this is in agreement with the findings of [11,18]. The pre-mixed fuel burns very fast and releases maximum heat followed by the controlled heat-release. With acetylene injection, the heat release rate is high for biofuel samples A1, A2, A3 and A4 compared to diesel fuel as a result of wide flammability limits and higher combustion rate of acetylene. The heat release rate during the premixed and uncontrolled combustion is thus accountable. In Fig. 5, there is a slight decrease in peak heat release for A1, A2, A3 and A4, this occurs as a result of inferior combustion properties/poor physical properties imposed in the oils, thus the biodiesel high cetane number reduces the ignition delay period, which in turn causes less accumulated fuel. For all the acetylene + air + BBMB samples, it was observed that best peak heat release rate (61 J/°) was obtained for sample A1 at 360°; other heat release rates for the blended samples were either lower or higher than this value, which in turn affected their combustion properties, thus giving higher BTEs for sample A1 relative to other BBMB-acetylene- air blended fuels. Although, sample A2 gave a similar crank angle of 61° with the diesel, however, this is only appropriate for the diesel unblended fuel. In addition, the addition of acetylene-air mix to the BBMB influenced the properties of the fuel blends, which in turn altered their HRRs such that, sample A1 gave the best peak HRR at crank angles greater than 360°.

Fig. 6 illustrates the variation between peak cylinder pressure and load for diesel and biofuel samples A1, A2, A3 and A4. The peak cylinder pressure range for diesel operation is between 65 and 71 bar for 0 to 100% load. The cylinder pressures obtained for the biofuels A1-4 range from 66 to 84 bar. This occurs as a result of increase in peak pressure of the diesel operation at 100% loading/ignition delay and this corroborates the findings of [8]. For full load, the peak cylinder pressures for acetylene injection are 79, 87, 88 and 84 bar respectively.

The ignition delay was measured by determining the time duration between the initiation of combustion and injection of fuel ion the diesel engine [33]. This is the time within which the first amount of fuel arrives the chamber, such that, the initial flame is detected in the spray. Ignition delay period may be physically/chemically influenced; the former involves vapour mixing of air with fuel after atomization, whereas, the latter is a pre-combustion condition. The variation between ignition delay and the load for different acetylene injection flow rates in BBMB is illustrated in Fig. 7. The diesel ignition delay occurs between 14 and 8.1° CA for 0 to 100% load for all acetylene-induced BBMB biodiesel, A1-4; the ignition delay increased at low loads but reduced at high loads compared to the diesel-only fuelled system this is in agreement with the findings of [29]. An increase in the flow rate of the acetylene induced microalgae biodiesel (AIMB) was obtained for increased gas internal diameter. The estimated ignition delays are 16.1, 15.2, 15 and 15.7 °CA for biofuel samples A1-A4 respectively. At low load condition, the ignition delays for all 4 samples were seen to be higher than that of the conventional diesel fuel due to failure of diesel to mix with air in the presence of C_2H_2. However, for 100% load, it may be as a result of valves overlapping and high diffusion rate of acetylene resulting in low ignition

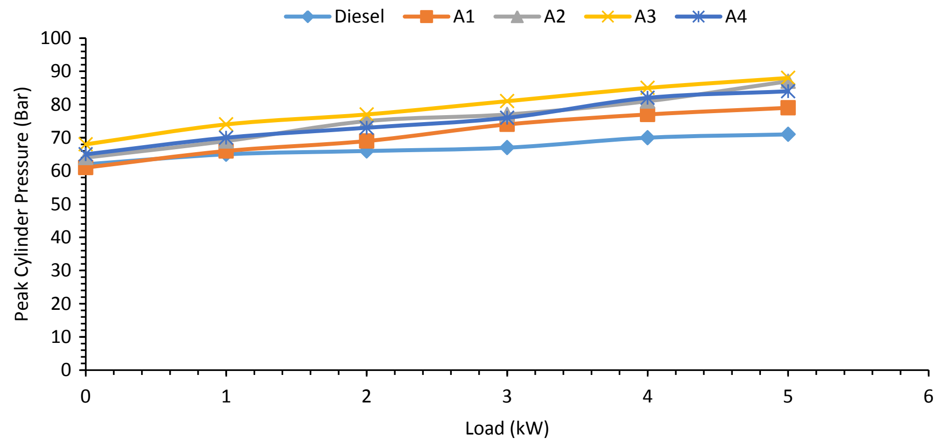

Fig. 6. Variation of Peak Cylinder Pressure with Load.

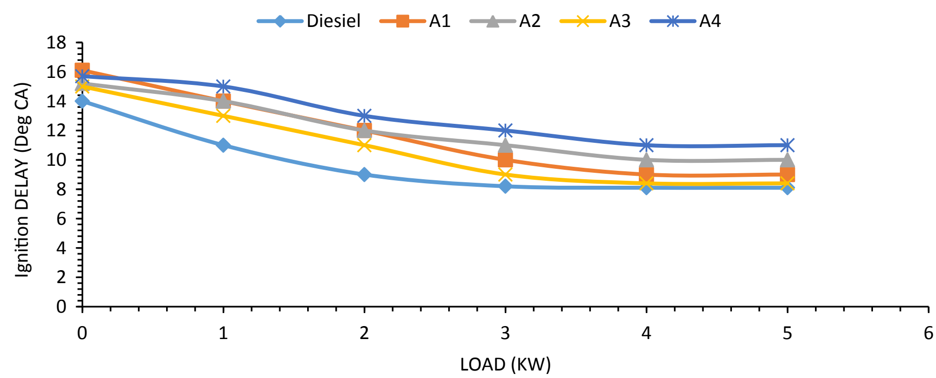

Fig. 7. Variation of Ignition Delay with load.

delays compared to the diesel-only fuelled process [26]. Although the BTE of the conventional diesel was highest, it had comparative efficiency with that of sample A1 up to 3 kW but showed slight variations between 3 and 5 kW engine power in Fig. 8; the influence can be seen to be better at lower flow rates since the best results were obtained for the sample injected with acetylene at 100 g/h.

Fig. 8 illustrates the variation of BTE for diesel and BBMB at different acetylene flow rates and brake power. The BTEs for all the biofuel samples A1-A4 are low compared with that of the conventional diesel fuel at all load conditions this agrees with the results of refs. [2,17,25]. At full load, the BTE for diesel and those of the samples are 33, 30, 29, 29.4 and 28% for samples A1-4 respectively. The BTEs for A1-4 are low as a result of poor combustion induced by poor physical properties. BBMB is known to have physical properties of high viscosity, high density, high pour point and high flash point which in turn affect its BTE, with resultant characteristics that include poor atomization, poor mixing with air and low peak pressure. However, the addition of acetylene-air mix in the BBMB helped to improve these properties which in turn influenced the recorded BTEs for the blended fuels; this is one of the novel contributions made on this subject because, from previous studies, BBMB has been reported to exhibit low BTEs than was obtained for the air-acetylene-BBMB fuel mix; please see Table 7 which shows the properties of the unblended BBMB and those of samples A1–A4 (Table 8). This affects the degree of atomization and vaporisation of the biofuels. In addition, the measured low calorific values of A1–A4 make them require an increase in the quantity of the fuel so as to produce same power output as obtained for the conventional diesel. The addition of oxyacetylene produced a rapid flame speed and wider flammability

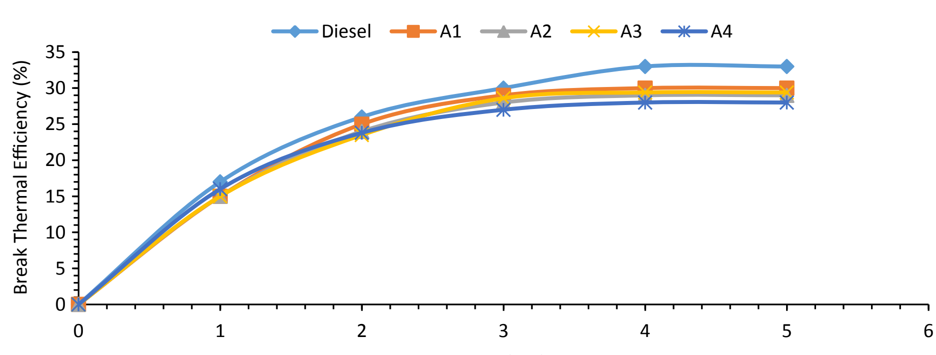

Fig. 8. Variation Brake Thermal Efficiency (BTE) with Load.

Table 8
Properties of BBMB/Acetylene blends

Parameter	Units	A1	A2	A3	A4
Pour point	°C	−1	−1	−2	−1
Kinematic viscosity @ 40	mm^2/s	2.32	2.37	2.42	2.40
Cloud point	°C	2	1	2	1
Flash point	°C	80.6	81.6	80.9	82.1
Calorific value	MJ/Kg	44.9	44.1	44.7	43.9
Cetane number	–	43.7	44	43.9	44.1
Density	Kg/m^3	822.5	824.1	822.3	823.0

which improved BTE performance of all biofuel samples as shown in Fig. 8; more so, this gives faster combustion rates for the biofuels, thereby reducing the pilot fuel which may lead to high heat transfer rate. Generally, in the dual-fuel engines, there is a decrease in the thermal efficiency at low loads, which then increases above the base line for 100% loading for an increase in mass flow rate of the induced biofuel. According to [27] LPG, CNG and other fuels with high loads and at different flow rates give reduced BTEs due to faster heat release and high diffusion rates of the fuels. Low efficiencies for partial loads usually occur in dual fuel operation due to poor combustion of the induced fuel – air mixture. However, fuels with wide limits of flammability and high flame velocity can minimize this effect (see Table 9).

The variation of exhaust gas temperature (EGT) with diesel fuel and BBMB at different flow rates of acetylene and engine load is illustrated in Fig. 9. When the EGT increases, it results in an increase in heat release for biofuel samples A1-A4 with confirmed improvements in their amounts of released energy in the cycle; the sample fuels also gave higher flame speed compared to that of the conventional diesel fuel due to the input of energy in the acetylene gas, which justifies the findings of [24]. In addition, the EGT for the BBMB in dual fuel mode operation is said to have been high compared to when the pure/conventional diesel was used due to NOx gases present in the fuel stream. Higher EGTs were recorded for the BBMB biodiesel fuel when used alone as sole fuel, as well as, when it was used in dual fuel mode operation. The EGT is between 120 °C and 310 °C for diesel fuels and 146 °C to 378 °C for the acetylene-air induced BBMB. The exhaust gas temperature attained 378 °C for A4 at full load compared to other fuel samples. The increase in EGT while injecting acetylene gas in the BBMB may be due to high release of heat by biodiesel, this is in line with the findings in Ref. [7]. EGT is vital for optimizing the acetylene gas location in the intake pipe along with air.

Fig. 10 demonstrates the variation of BSEC for the BBMB fuels at different flow rates of acetylene and brake power. The BSEC is the product of Brake Specific fuel consumption and its calorific value. In Fig. 10, the BSEC of the biodiesel induced with oxyacetylene at different flow rates is higher compared to that of the conventional diesel fuel. As the load increased, BSEC decreased. Better BSECs were achieved when the biodiesel was injected with oxyacetylene as shown in Fig. 10. BSECs for diesel and biofuels A1-A4 at full load condition are 9.3, 10.4, 10, 12 and 10.1 MJ/kWh respectively. The increase in BSEC for fuel samples A1-A4 can be linked to physical properties such as, viscosity, high density, and heating value, but, at higher compression ratios, low values of specific energy consumption are apparently desired [11,38]. Improved combustion efficiency and fast combustion rates are important in reducing the overall energy consumed by all the synthetic fuels.

CO causes severe contamination on human health [28–30]. The presence of CO in the exhaust gas is as a result of incomplete combustion, poor mixing and the existence of local rich regions etc. Minute quantities of CO also occur due to fuel spray quality and viscosity. Fig. 11 shows the variation of CO emissions with BBMB biodiesel fuels at different flow rates of acetylene and loading. The CO content for the biodiesels lie in the range of 0.000089775–0.0001759591 g/kWh and increases with acetylene-air addition at different flow rates. Small quantities of acetylene gas that replace air in the intake pipe could lead to less air in the pipe, thus allowing for improper combustion and the resulting mixture is then said to be fuel rich [38]. This results in having excess CO emissions using acetylene gas as fuel. Acetylene addition further reduces CO emission as a result of the low carbon content in C_2H_2 and higher combustion tendencies this is in line with the findings [12]. Increasing the time of combustion, cylindrical heat transfer reduction and excess oxygen present in the biodiesel are responsible for this reduction. However, CO increases as the fuel–air ratio becomes greater than the stoichiometric value. High in-cylinder temperature with acetylene addition stimulates faster oxidation of carbon monoxide to carbon dioxide, thus reducing CO emission at the exhaust; at full load condition, the CO emissions for samples A1-A4 are 0.02, 0.022, 0.024 and 0.025% respectively.

The variation of HC emissions with load is very important in determining emission behaviour of the engine as illustrated in Fig. 12. From observation, hydrocarbon emissions of the various blends are higher for the conventional diesel fuel. Due to the presence of oxygen in the biodiesel, the oxygen increases during combustion, which results in better combustion while releasing high HCs compared to diesel [37]. Hydrocarbon emission occurs in the combustion chamber due to flame quenching when air and fuel mix. The HC emission-concentration for the conventional diesel fuel is in the range of 0.052 to 0.034 g/kWh, however, for the acetylene-air induced fuel, the values are 0.064 to 0.046 g/kWh at full load condition. At full load, the HC emission is 0.034 g/kWh in baseline diesel operation and 0.044, 0.046, 0.048 and 0.046 g/kWh for samples A1, A2, A3 and A4, respectively when acetylene is aspirated ad mixed with BBMB at full load condition. In the case of dual fuel mode, HC emission reduction is due to the burning rate of oxyacetylene. It can also be due to the presence of oxygen in the biodiesel molecular structure, which oxidizes the unburnt HCs at high temperatures. However, the reduced carbon-hydrogen ratio with C_2H_2 also helps in reducing the hydrocarbon emissions for samples A1 and A2 relative to A3 and A4. Again, a closer look at Fig. 12 shows that sample A3 had the highest UHCs followed by sample A4. The reason is because, at high flow rate of 200–300 kg/h, there is less mass transfer/interaction between the diesel + air-acetylene mix, whereas, for the samples (A1-A2) with air flow rates of 100–150 kg/h the mass transfer is more effective as a result of the slower pace of the flowing air relative to the BBMB. Hence, with lesser interactions as depicted for samples A3 and A4, the fast-moving air does not allow for efficient combustion of the hydrocarbons, thus causing more UHCs to be released from the engine.

Fig. 13 shows the variation of NOx emissions with BBMB fuels at different flow rates of acetylene and engine load. As the load increases, the combustion gas temperature increases, thereby increasing the NOx formation in gram per kWh. In dual fuel operation, with acetylene-air induction, the NOx emissions increased at full load for both diesel and the biofuels (A1-A4). This is due to the enhancement in the rate of

Table 9
Summary of validated results by some researchers.

	Other works			This study	Remarks
Parameter					
BTE (%)	25–30 [25]	26–31 [10]	24–28[17]	28–30	At several load condition
HRR(J/°CA)	63–65 [12]	60–65 [11]	60–64 [10]	61–64	At several load condition
CO (g/kWh)	–	0.00009–0.00019 [12]	–	0.000089–0.000176	At several load condition
HC (g/kWh)	–	0.042–0.07 [9]	0.05–0.08 [18]	0.044–0.066	At several load condition

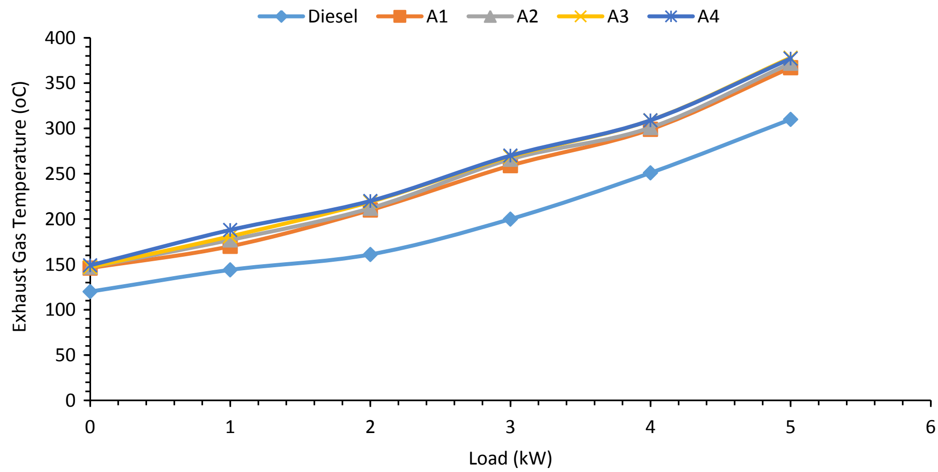

Fig 9. Exhaust Gas Temperature with Load.

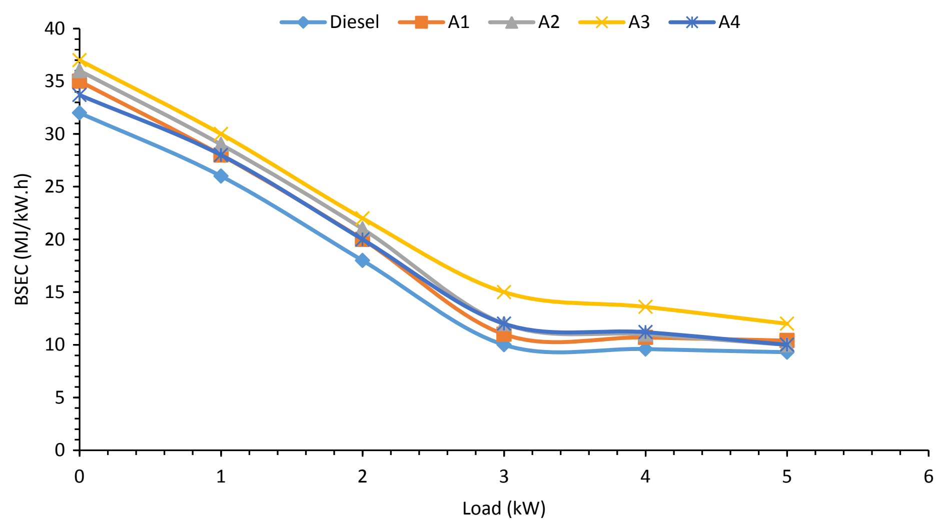

Fig. 10. Variation of Brake Specific Energy Consumption (BSEC) with Load.

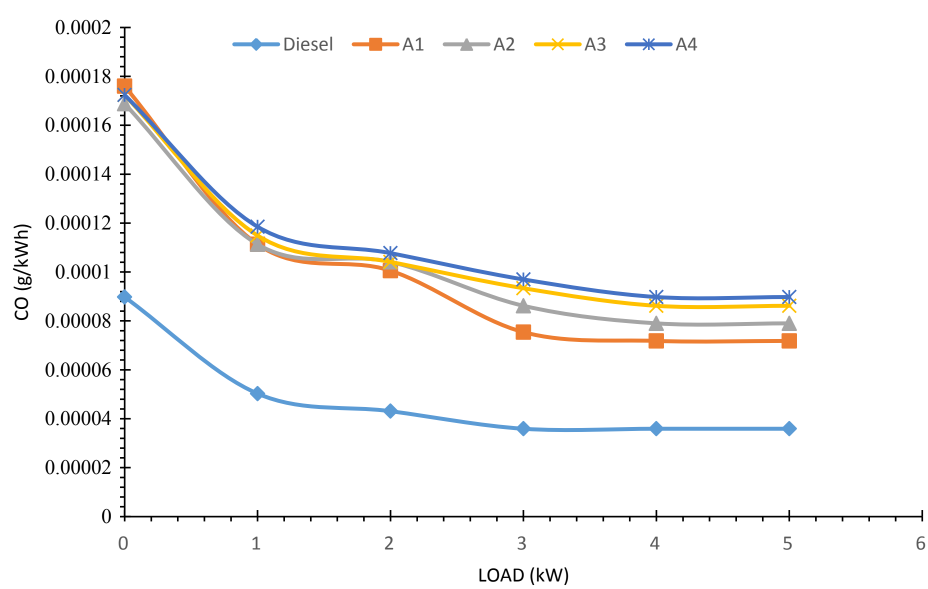

Fig. 11. Variation of CO with Load.

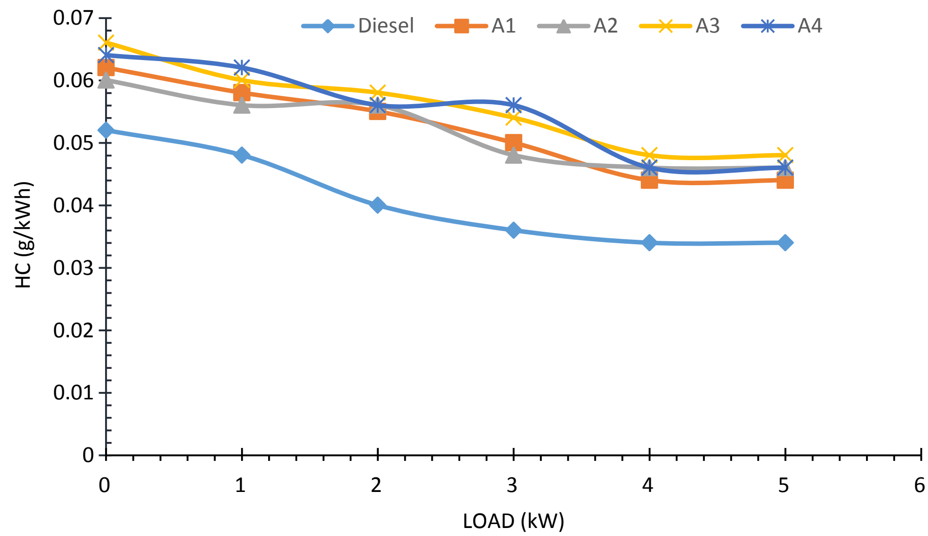

Fig. 12. Variation of Unburnt Hydrocarbons with Load.

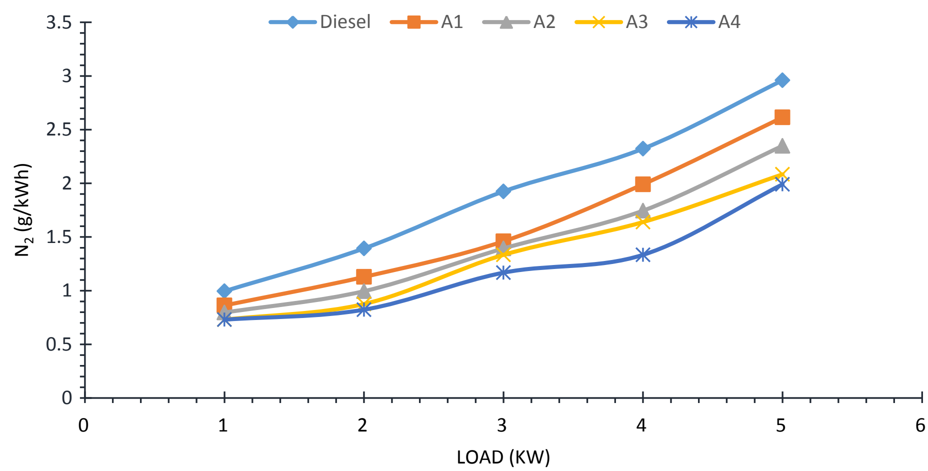

Fig. 13. Variation of NOx with Load.

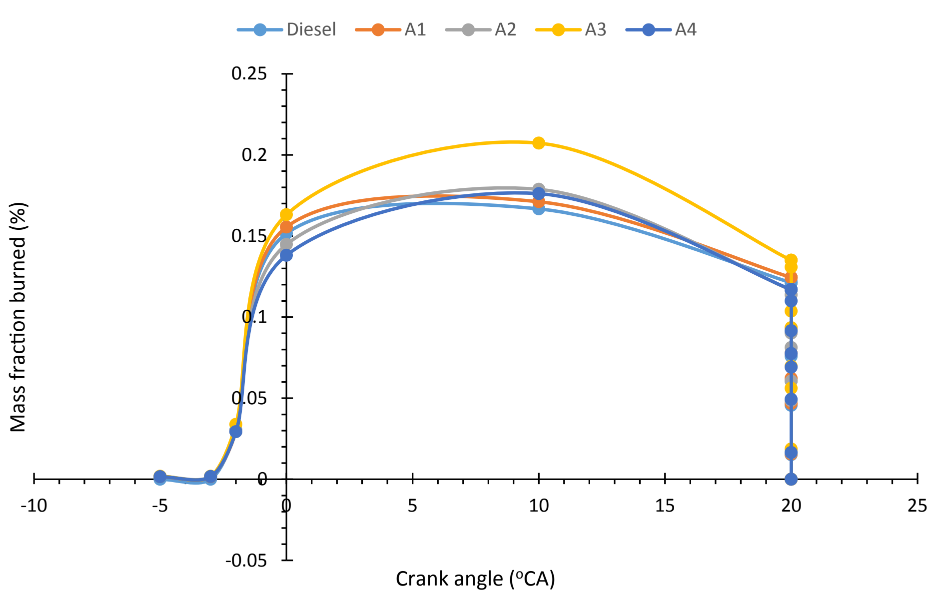

Fig. 14. Variation of mass fraction burned with crank angle.

combustion that causes increase in temperature, which results in an increase in NOx release. The released nitrogen during fuel combustion, reacts with oxygen to form nitrogen oxide; in excess oxygen, nitrogen (II) oxide is formed which can cause severe respiratory disease and photochemical smog. Fuel-air ratio and in-line cylinder pressure determine the emission rate of NOx in the exhaust. At 100% load, NOx emissions for diesel are in the range of 0.995 to 2.959446 g/kWh from no load to full load, while for the acetylene induced BBMB fuels, the values are 2.61, 2.35, 2.08 and 1.99 g/kWh for samples A1-4, respectively at full load condition. This is due to the oxy-acetylation of acetylene by air to form oxyacetylene which in turn improved the atomization properties of acetylene since ordinary acetylene in biofuels results in high NOx emissions as recorded in Ref. [39]. Also, owing to the fact that oxyacetylene has better combustion properties relative ordinary acetylene, the authors took advantage of mixing acetylene with air as a means of infusing acetylene with oxygen bond at various air–fuel ratios which helped to ensure high combustion potential and low availability of excess air for nitrogen conversion to NOx. The authors would like to also state clearly here, that this is one of the viable novel strategies adopted in this research.

Fig. 14 illustrates the variation of mass fraction of burned fuel at several crank angles for diesel and BBMB fuels at different flow rates of oxyacetylene. In the diesel, the mass fraction of burnt fuel is about 0.1667 at a crank angle of 10 °CA, while for the biodiesel samples A1-4, the peak value of mass fraction of the fuels burnt are 0.1711, 0.17873, 0.120725, and 0.17611, respectively at 10° CA. Higher biofuel mass fractions in the acetylene, leads to high flame speed and fast release of energy. High self-ignition temperature of oxyacetylene allows for larger compression ratios and due to high viscosity and lower calorific value of the fuels relative to that of conventional diesel when used in CI engines. Therefore, the mass fraction of biofuel-acetylene-air mix is relatively higher than that of diesel. The mass fractions of the fuels are in the following increasing order of magnitude: Diesel < A1 < A2 < A4 < A3; again, it is evident that for the fuel samples, sample A3 has the highest mass fraction due to its cylinder peak-pressure and heat release rate anomalies relative to other samples, as already discussed; from the ideal gas law, pressure is proportional to the number of moles of a gaseous component (i.e., the gaseous fuel). Furthermore, all the fuels have a maximum peak crank angle of 10°.

CO_2 in the atmosphere increases greenhouse gases and causes global warming [36]. High exposures to CO_2 can distort human health, with resultant ailments such as high blood pressure, convulsions, asphyxia etc. Fig. 15 shows a rising trend between the load and CO_2 emissions for the conventional diesel fuel and acetylene-air induced biofuel samples A1, A2, A3 and A4 at different flowrates. At full load, carbon dioxide emissions for A1-A4 are: 2.05, 3.16, 3.22, 3.3 and 3.06% respectively. Higher CO_2 emissions for biofuels A1, A2, A3 and A4 are attributed to the high carbon content of the biodiesels as well as the presence of excess oxygen. CO_2 emission reduces with acetylene-air injection due to possible carbon reduction by acetylene in the acetylene-air–fuel mix [37,38].

Proposed Mechanism/reaction scheme for the BBMB-acetylene-air mixture-formation

O_2 (Oxygen in air) + Acetylene oxyacetylene (intermediate product) + BBMB

Oxy-acetylated BBMB

The above mechanism clearly informs that oxyacetylene is first formed as an intermediate product of the reaction between acetylene and oxygen. The oxyacetylene was thereafter mixed with BBMB to give the oxy-acetylated BBMB fuels (A1-A4).

4. Conclusion

A 4-stroke (Kirloskar AV1) engine of 5.2 kW maximum load and 1500-rpm speed was operated successfully both on diesel and BBMB induced with acetylene-air mixture at different flow rates and load conditions. Experiments were conducted in order to determine the performance, combustion and emission characteristics of a CI engine operating on mixed fuel. Biodiesel produced from BBMB aspirated with oxyacetylene at different flowrates and 100% load, exhibits good engine performance compared to normal diesel fuel. There is an appreciable increase in BSFC at varying engine loads due to the addition of acetylene-air mix in the biodiesels with resultant decrease in their recorded BSECs. In dual fuel mode, and at full load, the recorded BTEs were lower than those of normal diesel fuel, due to continuous air-acetylene induction at the engine inlet.

The measured EGT at full load is higher than that of diesel fuel. Based on the results obtained from the flame tests conducted for the different fuel-blends, an air: acetylene ratio of 2:1 gave the best synergistic effect for air-acetylene mixture flow rates of 100–300 g/h, whereas, above a flowrate of 300 g/h, the blends gave poor flame properties. For the conventional diesel fuel, at 100% load, the recorded NOx emissions were in the range of 0.995–2.959446 g/kWh from minimum to full load condition, while for the acetylene-air induced BBMB fuels, the estimated NOx emissions are 2.61, 2.35, 2.08 and 1.99 g/kWh for samples A1-4, respectively under the same conditions of minimum and full load. This then gives credence to the importance of oxy-acetylation of the acetylene for improved atomization, because, based on some reports, the use of ordinary acetylene in biofuels, may give rise high NOx emissions. For the UHCs, it was observed that sample A3 had the highest UHCs followed by sample A4 and this was caused by their higher flow rates (i.e., 200–300 kg/h) relative to those of other samples, thus leading to low mass transfer/interaction between the diesel and the oxyacetylene when mixed. However, for the samples A1 and A2 whose air flow rates are 100 and 150 kg/h respectively, mass transfer was more effective/higher as a result of the slower pace of the flowing air relative to the BBMB. Hence, with lesser interactions fast-moving air molecules will not allow for efficient combustion of hydrocarbons, which in turn results in the escape

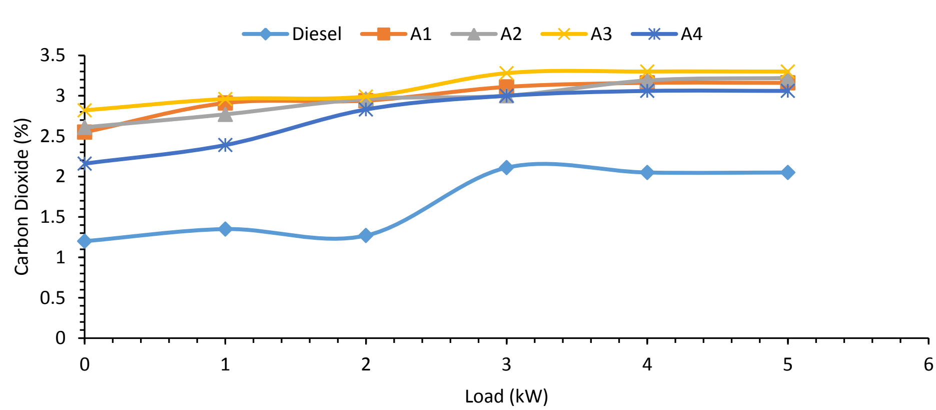

Fig. 15. Variation of CO_2 with Load.

of UHCs via the exhaust. BBMB is characterized by high viscosity, high density, high pour and flash points, which have negative consequences on its BTE, as well as poor atomization, poor mixing alongside low air and peak pressures. Hence, the inclusion of acetylene-air mix in the BBMB improved/modified these properties, thus resulting in improved BTEs for the blended fuels at varying air-acetylene flow rates. For all the acetylene + air + BBMB samples, the best peak HHR (61 J/°CA) was obtained for the fuel-blend A1 at 360 °CA; other heat release rates for the blended samples were either lower or higher which affected their combustion properties thus resulting in higher BTEs for sample A1 compared to other BBMB-acetylene-air fuel-blends. The crank angle of sample A2 (61°) is similar to that obtained for the unblended diesel fuel. Also, the mixing of the acetylene-air mix with BBMB, altered the inherent characteristics of the blended fuels, which in turn influenced their HRRs such that sample A1 gave the best peak HRR at higher crank angles greater than 360°. For samples A1, A2 and A4, the reduction in peak HRR was evident except for sample A3, whose cylinder pressure peak pressure increased. The low peak pressures of A1, A2 and A4 were caused by the low heat release rates recorded for the samples beyond 330° as compared to samples A4 and that of the conventional biodiesel. Furthermore, there is an appreciable reduction in HCs, CO_2 and CO emissions as observed with the oxy-acetylated fuels, however, NOx emission increased in the air-acetylene induced biodiesels, due to high flammability of acetylene. The peak cylinder pressure increased due to the inclusion of acetylene gas. Furthermore, the performance of BBMB was also enhanced by the addition of the air-acetylene. Therefore, BBMB induced with oxyacetylene can be used as a replacement for diesel fuel in CI engines owing to its improved combustion, performance and emission characteristics compared with ordinary BBMB or BBMB-acetylene-induced fuels.

Potential applications of the blended-fuel include the following, to:

1. improve the potential of commercialization and use of BBMB as fuel for CI engines
2. improve the combustion potential of BBMB in CI engines
3. reduce environmental pollution resulting from NOx, CO and HC emissions which may have grave consequences on humans, aquatic life and the environment.
4. enhance the engine performance of BBMB using air and acetylene as additives, rather than acetylene as the only additive, when used in CI engines.
5. produce an ideal air-acetylene-BBMB mix that will optimize the power consumption of the engine.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.fuel.2021.120675.

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