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**Article**

## The utilization of n-butanol

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## Research paper

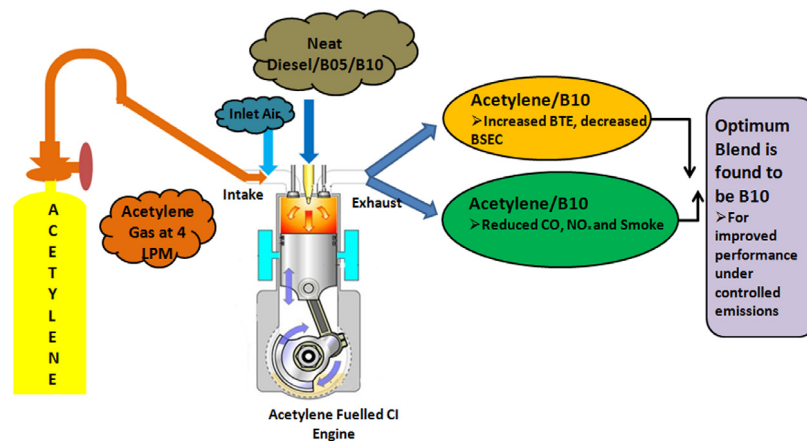
## The utilization of n-butanol/diesel blends in Acetylene Dual Fuel Engine

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## HIGHLIGHTS

- n-butanol/diesel blend up to 10% can be utilized in acetylene fuelled CI engine without major modification.
- Addition of n-butanol improves combustion characteristics followed by the performance.
- Lower emissions of NO<sub>x</sub>, CO and smoke emissions with a marginal penalty of HC emissions.

## GRAPHICAL ABSTRACT



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## ABSTRACT

Ever-growing energy demand has motivated engine researchers to find eco-friendly and sustainable cleaner fuels for diesel engines. Many scientists have used different oxygenated additives to enhance the performance of the acetylene fuelled diesel engine, whereas no work has been found in the literature to utilize n-butanol as an additive in acetylene dual-fuel engine. Hence, considering this important literature gap, the author has investigated the effect of n-butanol in acetylene fuelled CI engine by analysing combustion, performance and emission parameters. In the current study, an experimental investigation has been conducted on a modified diesel engine in which acetylene is being inducted at 4 LPM whereas neat diesel, B05, and B10 blend was used as a pilot fuel for different loads. The results show that when the proportion of n-butanol is increased to 10% the BTE increases by 2% than normal diesel at full load, maybe due to sufficient amount of oxygen available to combust whole acetylene-air mixture. BSEC increases marginally during acetylene induction due to the higher flame velocity of acetylene. The EGT is lower than normal diesel for entire loading conditions while running the engine on dual fuel mode. The highest value of peak cylinder pressure is 77.87 bar and the HRR is 53 J/°CA when the B10 fuel is injected as pilot fuel. Moreover, CO value reduces by 23% than baseline diesel at maximum load whereas HC increases by 8% than normal diesel at full loading conditions. However, NO<sub>x</sub> reduces considerably i.e. 18% lower than neat diesel at peak loads, while injecting B10 blend this may be due to the higher latent heat of vaporization of n-butanol/ diesel blend causes reduced combustion temperature. The smoke opacity is lowest i.e. 44% lower than normal diesel at maximum load while injecting B10 blend in DFE. The percentage energy shared by acetylene

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varies from 60% to 31% for zero loads to peak load while utilizing B10 blend as pilot fuel furthermore consumption of diesel was reduced significantly by 32% at maximum load. Overall, it can be concluded that 10% of n-butanol can be blend with neat diesel for efficient utilization of acetylene in DFE.

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## 1. Introduction

Diesel engines are the most reliable engines used in different areas for example transportation system, agricultural machines, and in power industry due to its increased efficiency, lesser fuel consumption, lower fuel price, and durability (Kumar et al., 2013). Meanwhile, the major challenges of these engines are harmful exhaust emissions, which are severely affecting biodiversity and ecosystem from so many years (Johnson, 2009). Furthermore, the consumption of petroleum fuels has reached a critical stage because of the rapid inclined in on-road vehicles (Geng et al., 2017). Hence, to mitigate over-dependency of crude oil and to protect the environment from harmful pollutants engine researchers are trying to find low emissions alternative renewable fuel (Othman et al., 2017). Most of the scientists have suggested by utilizing renewable fuel the twin catastrophe i.e. dwindling of fossil fuels reserves and environmental degradation can be controlled (Rajasekar et al., 2010; Mofijur et al., 2015). Most of the engines designers have modified conventional compression ignition (CI) engine to operate the engine on dual-fuel combustion mode by changing its hardware slightly (Kumar and Kumar, 2016). Engine researchers have found that by upgrading normal engine to dual-fuel engine (DFE) the performance characteristics have improved marginally meanwhile exhaust emissions were reduced substantially relative to a baseline diesel engine (Srivastava et al., 2017; Behera et al., 2014). Moreover, many scientists have highlighted the major drawback of DFE is a higher rate of NO<sub>x</sub> emissions as well as increased fuel consumption at medium to high loads (Lakshmanan and Nagarajan, 2011a, 2010b). Different types of a gaseous fuel such as hydrogen, CNG, LPG, biogas, syngas, and acetylene have been utilized in DFE engines by various engine experts (Dimitriou and Tsujimura, 2017; Wei and Geng, 2016; Ashok et al., 2015; Sahoo et al., 2009; Wulff et al., 2001). According to existing literature survey, most of the work has been concentrated on CNG and hydrogen (Dimitriou and Tsujimura, 2017; Wei and Geng, 2016) however very less quantum of work has been explored to utilize acetylene as a primary fuel in CI engine. Engine experts have highlighted the significant combustion properties such as wider flammability limits, higher self-ignition temperature and higher calorific value of acetylene which make acetylene more promising fuel for diesel engine (Basha et al., 2017; Sharma et al., 2012; Basha et al., 2016a). Many engine researchers have also quoted by consuming acetylene the problems like black exhaust, wall wetting and lower lubricity in CI engines can be resolved (Khader Basha and Rao, 2016; Basha et al., 2016b; Choudhary and Nayyar, 2013). Furthermore, acetylene is much cheaper than hydrogen and not as much explosive as hydrogen is hence, acetylene can be used easily as in CI engine as an alternate fuel (Valmiki, 2016; Behera and Murugan, 2013; Sudheer and Nagaraj, 2016). Meanwhile, many researchers have also quoted it has potential to substitute petroleum diesel in the near future (Basha et al., 2017; Sharma et al., 2012; Basha et al., 2016a; Khader Basha and Rao, 2016; Basha et al., 2016b; Choudhary and Nayyar, 2013; Valmiki, 2016; Behera and Murugan, 2013; Sudheer and Nagaraj, 2016). To prevent accidental hazards, the major safety procedures should be followed while handling acetylene in CI engine (Price, 2006). The properties of acetylene have been compared with hydrogen and neat diesel in Table 1.

The maximum number of literature has highlighted cheaper and viable techniques for acetylene production is from calcium carbonate (limestone) and water (Mahla et al., 2012; Schobert, 2014; Parthasarathy et al., 2014). The place where limestone is abrupt, one can easily produce acetylene gas and utilize it as a prime fuel at consumption sites of limestone, mining areas, and cement industry (Lakshmanan and Nagarajan, 2010a). Few scientists have also proposed a renewable method for acetylene production is done by thermal cracking of methane (Schobert, 2014), but the initial investment may be too high for this modern technique however after mass production, it is expected that the production cost may reduce significantly. Most of the engine researchers have preferred dual-fuel combustion (DFC) technique over the HCCI method to address the controllability and high HRR issues during the combustion process and recommended DFC as one of the prominent methods for conserving conventional petroleum fossil fuels (Behera et al., 2014; Behera and Murugan, 2013; Lakshmanan and Nagarajan, 2010a). Most of the scientists have optimized the flow rate of acetylene under different loads by analysing the emission and performance parameters (Behera et al., 2014; Lakshmanan and Nagarajan, 2011a, 2010b; Basha et al., 2016a; Khader Basha and Rao, 2016; Basha et al., 2016b; Choudhary and Nayyar, 2013; Valmiki, 2016; Behera and Murugan, 2013; Sudheer and Nagaraj, 2016). Many authors have suggested by inducting acetylene in diesel engine, thermal efficiency reduces marginally (Sharma et al., 2012; Basha et al., 2016a; Khader Basha and Rao, 2016; Basha et al., 2016b; Choudhary and Nayyar, 2013; Valmiki, 2016) whereas some of them have also reported thermal efficiency improves significantly by modifying injection techniques in DFE (Behera et al., 2014; Lakshmanan and Nagarajan, 2011a, 2010a). Few of the literature also suggests by employing EGR techniques NO<sub>x</sub> and smoke can be reduced drastically but at the same time, some penalties can be also seen in form increasing rate of HC and CO pollutants (Lakshmanan and Nagarajan, 2011b; Sudheesh and Mallikarjuna, 2010a; Swami Nathan et al., 2010). Many researchers have also injected water to improve performance as well as reduce exhaust emissions (Lakshmanan et al., 2013; Sudheesh and Mallikarjuna, 2010b). Most of the scientists have used diesel as pilot fuel for acetylene DFE (Wulff et al., 2001; Basha et al., 2017; Sharma et al., 2012; Basha et al., 2016a; Khader Basha and Rao, 2016) whereas very little quantum of work has been done to utilize oxygenated blend in acetylene fuelled CI engine (Sudheesh and Mallikarjuna, 2015; Brusca et al., 2014). Many scientists have observed that biodiesel acetylene fuelled DFE has lower thermal efficiency than neat diesel while NO<sub>x</sub> increases significantly at higher loads (Valmiki, 2016; Sudheer and Nagaraj, 2016; Parthasarathy et al., 2014) however few of the engine experts have also found improved performance as well as reduced NO<sub>x</sub> during acetylene induction with biodiesel (Behera et al., 2014; Behera and Murugan, 2013). Many researchers have recommended that by blending oxygenated biofuel such as alcohol and di-ethyl ether (DEE) up to 20% thermal efficiency of CI engine may be enhanced (Mahla et al., 2012; Agarwal, 2007; Cinar et al., 2010; Karabektas et al., 2014). Most of the research has been concentrated on traditional alcohols such as methanol and ethanol blends in CI engines (Zhen and Wang, 2015; Verhelst et al., 2019; Hansen et al., 2005; Shahir et al., 2015; Coulier and Verhelst, 2016) however very less quantum of work has been explored on the utilization of higher-order alcohols like butanol (No, 2016).

Table 1

SN.	Properties	Diesel	Hydrogen	Acetylene	Butanol
1	Formula	C <sub>12</sub> H <sub>26</sub>	H <sub>2</sub>	C <sub>2</sub> H <sub>2</sub>	C <sub>4</sub> H <sub>9</sub> OH
2	Auto ignition temperature (K)	530	858	578	658
3	Flammability limits (vol% in air)	0.7–5	4–75	NA	1.45–11.2%
4	Stoichiometric air–fuel ratio	14.5	34.3	13.2	11.2
5	Molecular weight	170	2.016	NA	74.12
6	Density (kg/m <sup>3</sup> )	833–881	0.09	1.092	810
7	Net heating value (MJ/kg)	43.5	120	48.2	33.2
8	Flame velocity (cm/s)	30	265–325	150	NA
9	Boiling point (K)	436–672	20.27	NA	390
10	Adiabatic flame temperature (K)	2200	2400	2500	2246

Many engine experts have considered n-butanol more advantageous than lower carbon alcohols like methanol and ethanol because of its higher calorific value very close to neat diesel, better miscibility with petroleum diesel, inferior viscosity and flash point tends to improve the atomization of fuel, inferior latent heat of vaporization (LHV), lower density, enhanced blending stability, less prone to moisture, less explosive, higher cetane number and moreover its auto-ignition temperature is also lesser than lower-order alcohol, therefore, it makes butanol more suitable additive for diesel fuel (No, 2016; Chao et al., 2011; Rajesh Kumar and Saravanan, 2016). Many engine scientists have quoted that butanol can be considered as futuristic biofuel obtained by the utilization of wastage of food as well as from the biomes, eukaryotic bioorganisms and other plant constituents having cellulose (Cheng et al., 2012; Kumari and Singh, 2018; Maiti et al., 2016). However, it is challenging to use butanol as a primary fuel in CI engines because of its lower heating value and lower cetane number (No, 2016; Chao et al., 2011; Rajesh Kumar and Saravanan, 2016). Recently very efficient techniques for the production of n-butanol have been developed and it is expected that higher production rate of n-butanol will be achieved in the coming years (Gu et al., 2011; Malaviya et al., 2012; Jin et al., 2011). Many scientists have explored the effects of n-butanol–diesel blends by varying the percentage of n-butanol in CI engine (Goga et al., 2019; Rakopoulos et al., 2010a; Campos-Fernández et al., 2012; Zhang and Balasubramanian, 2014; Rakopoulos et al., 2011, 2010b). Most of the researchers have observed that by adding n-butanol in neat diesel soot, nanoparticles and CO emissions reduces significantly without any change in the BSFC and NO<sub>x</sub> (Goga et al., 2019). Many engine experts have found that by increasing n-butanol proportion, the ignition delay was increased moreover peak pressure rise also increases with marginal inclined in the BTE (Rakopoulos et al., 2010a; Campos-Fernández et al., 2012; Zhang and Balasubramanian, 2014). Few of the engine researchers have also found that adding n-butanol up to 20% in neat diesel enhances BTE as well as improves BSFC relative to petroleum diesel meanwhile slight reduction in NO<sub>x</sub>, CO, HC, and smoke was observed at higher loads (Rakopoulos et al., 2011, 2010b; Yao et al., 2010; Imtenan et al., 2015; Zhang et al., 2012; Rakopoulos et al., 2016; Zhu et al., 2014). Atmanli and Yilmaz suggested that n-butanol and 1-pentanol blends can be blended up to 35% with neat diesel for satisfactory operations (Atmanli and Yilmaz, 2018). Few scientists have compared acetone–n-butanol–ethanol (ABE) and isopropanol–n-butanol–ethanol (IBE) gasoline blends in SI engine and found that IBE blends were superior to ABE blends because of advanced combustion phasing and shorter combustion duration (Li et al., 2018). Lee et al. has explored the prospects of ABE as an alternative fuel for the near future (Li et al., 2019). Many scientists have recommended PFI technique to reduce NO<sub>x</sub> and to enhance the thermal efficiency of the CI engine at low loading conditions (Soloiu et al., 2013; Chen et al., 2013). Furthermore, from the literature survey, it can be clearly observed that very less quantum of work has been initiated by different researchers to utilize n-butanol/diesel blend in dual fuel CI engine.

Hence the author has considered this important literature gap and was motivated to study the effect of n-butanol in acetylene fuelled Diesel engine as the main objective of the present study. In the current experimentation, the author has selected acetylene as a primary fuel while n-butanol diesel blends as a pilot fuel to find out the optimized blend ratio of n-butanol/ diesel blend for improved performance under controlled emissions. The present study includes the assessment of acetylene DFE by investigating the combustion, performance and emission characteristics at different loads. The conventional CI engine was slightly modified to operate on dual-fuel combustion mode. Acetylene was supplied continuously at the flow rate of 4 LPM by the help of standardized gas flow meter into the engine cylinder. Since the self-ignition temperature of acetylene is very high so, it cannot ignite itself even at a high compression ratio (Behera et al., 2014; Lakshmanan and Nagarajan, 2011a, 2010b). Thus to ignite acetylene mixture properly the very small quantity of n-butanol/diesel blend was introduced at the end of the compression stroke. This acts as a primary source of igniting the whole combustible gas–air mixture. The ignition of gaseous fuel initiates because of flame spread by the pilot fuel inside the combustion chamber (Lakshmanan and Nagarajan, 2010a). Finally, the burning takes place similar to the gasoline engine (Behera et al., 2014; Behera and Murugan, 2013). Hence, the dual-fuel engine has both features of CI as well as the gasoline engine. The working of the acetylene fuelled diesel engine can be seen clearly in Fig. 1.

## 2. Experimental setup

A series of trials were done to examine the effect of n-butanol/diesel fuel blends in Kirloskar modified CAF8 acetylene dual-fuelled CI engine at a constant speed of 1500 rpm, the injection pressure of 220 bar and injection angle of 23° BTDC. The experimental setup consists of a modified CI engine, dynamometer, liquid flow measuring device, gas flow meter, K type thermocouple pressure transducer, crank angle encoder, AVL di-gas analyzer, smoke meter, and the data acquisition (DAQ) system. The detailed engine specifications are demonstrated in Table 2.

The speed of the engine, torque and brake power was measured by the help of DC dynamometer. The test engine was modified slightly to operate on dual fuel mode by inducting acetylene at a continuous stream of 4 LPM by the help of gas flow meter. The discharge pressure is maintained at 0.7 bar with the help of a double-stage pressure regulator. To avoid severe cases such as backfiring and overheating, and assuring smooth operation, flame arrestor, and the flame trap was used. Air was introduced in the mixing chamber moreover the intake of air was measured using an airflow sensor connected to the air intake. The quantity of pilot fuel was measured by a calibrated burette and a stopwatch. The EGT was measured by K type thermocouple attached to the exhaust end of the engine. The pressure transducer was mounted on the engine head to record the cylinder

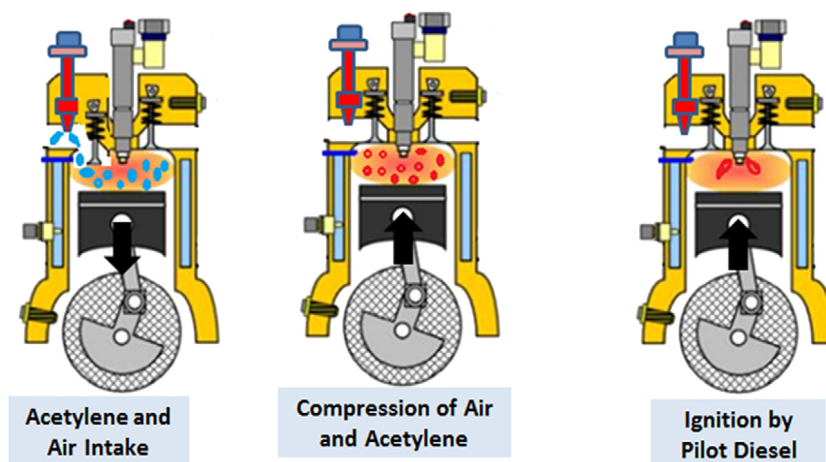


Fig. 1. Working of dual fuel engine.

Table 2

Engine specification.

Manufactured by	Kirloskar
Model	CAF8
Engine type	Single Cylinder, Vertical, CI, 4 Stroke
BP	4.4 kW
Type of cooling	Air cooling
Inlet valve open before TDC	4.5°
Inlet valve closes after BDC	35.5°
Exhaust valve open before BDC	35.5°
Exhaust valve closes after TDC	4.5°
Injection angle	23° BTDC
Injection pressure	220 bar
CR	17.5:1
Bore diameter	87.5 mm
Stroke length	110 mm
Cubic capacity	0.661 l
Rated speed	1500 rpm
Combustion system	Direct injection
Fuel tank capacity	6.5 l
Rated output	5.9 kW
Lubricating oil	SAE 20W40

pressure data whereas the crank angle encoder was fixed on the output shaft to locate the crank position. It was observed that the maximum fuel line pressure was at 370 °CA. Hence pressures peaks variations versus crank angle were measured. AVL DI-gas analyzer was used to obtain the exhaust gas pollutants such as HC, CO, and NO<sub>x</sub> whereas smoke emission was measured by AVL smoke meter. Finally, the (DAQ) system was used to gather and process all the inputs obtained from different sensors. The graphic layout of the experimentation engine is shown in Fig. 2.

All the obtained results were plotted and compared with the help of graphical representation. The experimentation trials were repeated at least thrice for each load. To get more accurate results uncertainty analysis was done by using the Holman technique. The calculation includes all the errors that arise from the required instrument, experimental condition, and observation of results, evaluation, and interpretation of test results. The total uncertainty percentage of this experiment was approximately 2 which consist of numerous constraints and is represented in Table 3.

Initially, experimentation was done by using petroleum diesel fuel to prepare the baseline data when the steady-state was achieved, and it is noted as D in all the figures. Then, n-butanol/diesel blends B05 (5% n-butanol + 95% diesel by volume basis) and B10 (10% n-butanol + 90% diesel by volume basis) were prepared and were used as pilot fuels under same conditions for comparative study with baseline diesel. Neat diesel, acetylene gas

and n-butanol were procured from a local supplier. The mass flow rate of acetylene was maintained constant for different loading conditions and the percentage of energy contribution of acetylene was evaluated for entire loads. Fig. 3 shows the percentage of energy share of acetylene at different loads. The heating value of diesel and acetylene is 43.8 MJ/kg and 48.22 MJ/kg respectively. Earlier when the engine is running on normal diesel the input heat energy of diesel is converted into brake power. Moreover, when acetylene is inducted during dual fuel mode, now a certain portion of the input energy is also contributed by acetylene and thus while operating on dual fuel mode diesel intake is reduced considerably for constant output power. The energy contributed by acetylene while inducting acetylene gas at 4 LPM during dual fuel mode with optimized induction length of 50 cm was 41% to 22% from zero loads to peak load and consumption of diesel was reduced by 23% at maximum load. Similarly, when B05 blend was used as pilot fuel the percentage of energy shared varies from 55% to 29% for no load to peak load and consumption of diesel was reduced by 30% at high load. Further, increasing the blend ratio to B10 the energy contributed by acetylene varies from 60% to 31% for zero loads to peak load and consumption of diesel was reduced by 32% at maximum load.

### 3. Results and discussion

The combustion, performance and emission parameters of acetylene DFE were investigated with a constant flow rate of acetylene at 4 LPM whereas different blend ratio (B05 and B10) of diesel/n-butanol blends and neat diesel were used as pilot fuel. The results obtained were analysed and compared with the petroleum diesel fuel for the entire loading range to draw the conclusion.

#### 3.1. Combustion parameters

In-cylinder pressure, heat release rate and ignition delay were evaluated for different blends as an ignition source in acetylene DFE.

##### 3.1.1. In-cylinder pressure

The deviation of peak cylinder pressure with changing crank angle is shown in Fig. 4. For normal diesel engine the peak pressure is 73.40 bar at full load whereas while inducting acetylene at a constant flow rate of 4 LPM for different pilot fuels, the peak pressure is 74.14 bar for acetylene–diesel DFE, 76.14 bar for B05 blend acetylene DFE and 77.87 bar for B10 blend acetylene fuelled

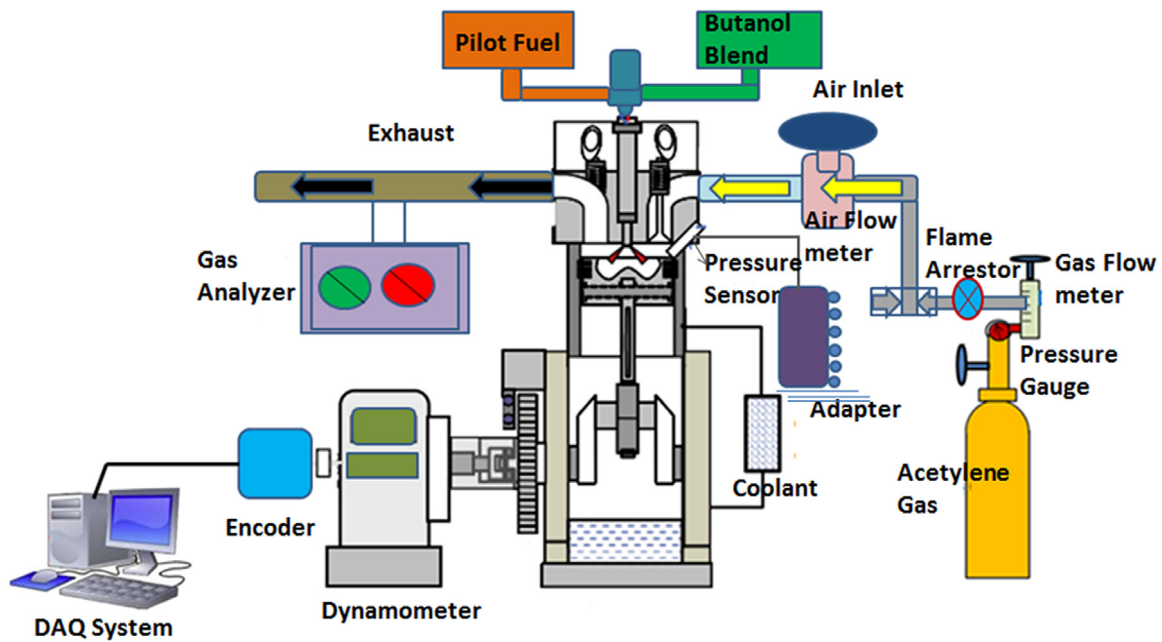


Fig. 2. Experimental setup.

Table 3

Total uncertainty percentage of the experiment.

Instruments	Range	Accuracy	Uncertainties (%)
AVL DI Gas 444 Exhaust gas analyzer	HC	0–10000 ppm	±20 ppm
	CO	0–10%	±0.03%
	NO <sub>x</sub>	0–5000 ppm	±50 ppm
AVL GH14d/AH1 pressure transducer		0–100 bar	±0.1 bar
	Exhaust gas temperature	0–900 °C	±1 °C
Speed measuring unit	0–100000 rpm	±10 rpm	±0.10
Burette measurement	0–100 cc	±0.1 cc	±1
Digital watch		±0.6 s	±0.20
AVL 365C crank angle encoder	0–720°		±0.20
Calculated BMEP			±0.60
Calculated BSEC			±0.50
Calculated BTE			±0.50

CI engine. The maximum rise of pressure rate is observed when B10 blend is injected in acetylene DFE, this might be due to the increased amount of oxygenated fuels, elevates the combustion temperature leading to high rise in pressure peaks also may cause higher HRR at this position. The peak cylinder pressure for acetylene DFE is forwarded around 5° to 8 °CA compared to neat diesel. The progression in peak pressure during acetylene induction is possibly due to instantaneous combustion in acetylene DFE. Similar outcomes were revealed in various literature (Behera et al., 2014; Behera and Murugan, 2013; Lakshmanan and Nagarajan, 2010a; Rakopoulos et al., 2010a; Campos-Fernández et al., 2012; Zhang and Balasubramanian, 2014; Rakopoulos et al., 2011, 2010b; Yao et al., 2010).

### 3.1.2. Heat release rate

The obtained result shows the normal pressure deviation considered for 100 cycles inside the engine cylinder. Fig. 5 illustrates the variation of HRR versus crank angle. The peak HRR for neat diesel is 51.41 J/°CA whereas, when acetylene is inducted in dual fuel mode with different pilot fuels, the value of HRR is 49.64 J/°CA for petroleum diesel as pilot fuel, 51.5 J/°CA for B05 blend as pilot fuel and 53. J/°CA for B10 blend as pilot fuel. The maximum value of HRR for dual fuel engine is observed when the B10 blend is introduced as pilot fuel, at this stage may be due to the higher quantity of acetylene fuel participates in combustion process eventually increasing peak pressure.

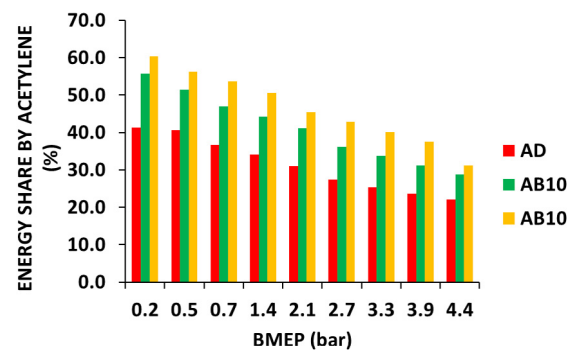


Fig. 3. Energy share of acetylene at different loads.

A similar observation has been observed during pressure versus crank angle graph. Hence it can also be concluded that the presence of n-butanol in acetylene fuelled CI engine shows dominant premixed combustion stage with a slight reduction in a diffusion flame, due to this BTE also improves. Similar findings were mentioned in various pieces of literature (Srivastava et al., 2017; Behera et al., 2014; Lakshmanan and Nagarajan, 2011a; Rakopoulos et al., 2010a; Campos-Fernández et al., 2012; Zhang

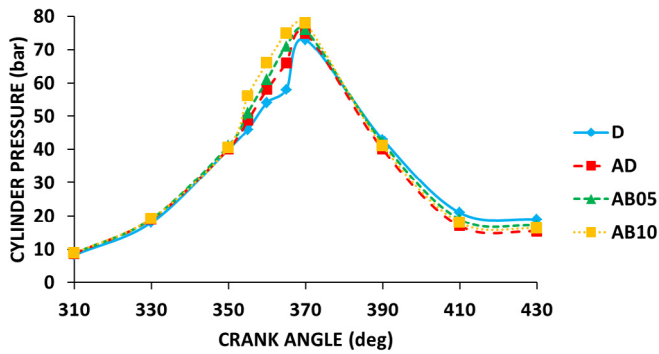


Fig. 4. Variation of cylinder pressure with crank angle.

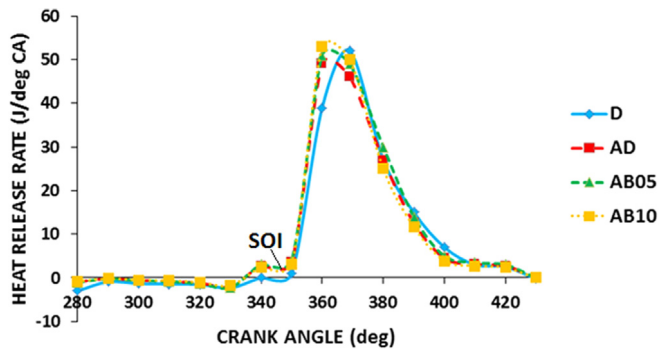


Fig. 5. Variation of HRR with crank angle.

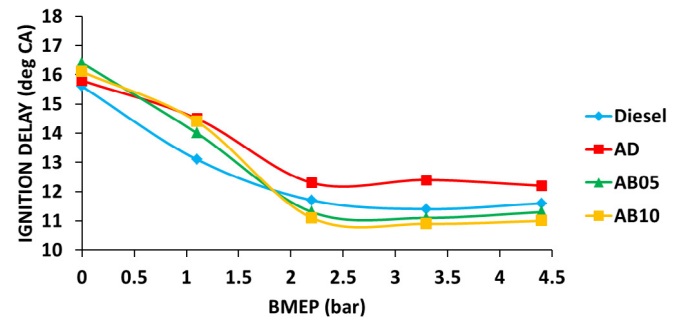


Fig. 6. Variation of ignition delay with BMEP.

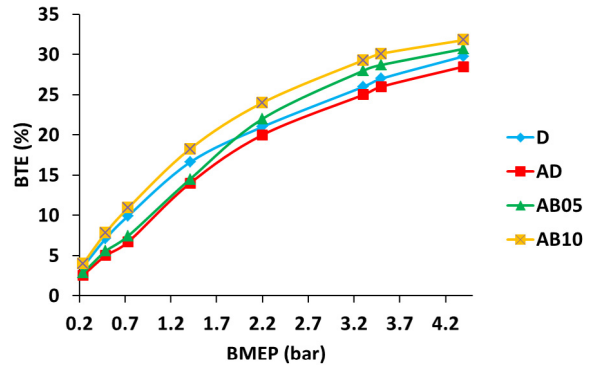


Fig. 7. Variation of BTE with BMEP.

and Balasubramanian, 2014; Rakopoulos et al., 2011, 2010b; Yao et al., 2010).

### 3.1.3. Ignition delay

The ignition delay (ID) period is the time difference between the start of fuel injection and the initiation of the ignition process. Fig. 6 shows the variation of ignition delay with a change in BMEP. For normal diesel mode, the ignition delay changes from 15.6 °CA at zero loads to 11.6 °CA at peak load. Meanwhile, when acetylene is inducted during dual fuel mode the ignition delay remains higher for the entire loading range this might be due to improper mixing of liquid pilot fuel with air during acetylene induction. The values of ID for acetylene induction at full load were 12.2 °CA, 11.4 °CA and 11.1 °CA while injecting diesel, B05 blend, and B10 blend as a pilot fuel in DFE respectively. The reason might be due to the low cetane index of the n-butanol/diesel blend and higher burning velocity causing prolonged ignition delay. Similar inferences were observed in many kinds of literature (Srivastava et al., 2017; Behera et al., 2014; Lakshmanan and Nagarajan, 2011a; Behera and Murugan, 2013; Lakshmanan and Nagarajan, 2010a).

### 3.2. Performance parameters

Performance usually measures how well an engine is converting input energy into the desired output work. To understand in detail about the engine performance the author had calculated BTE, BSEC and measured EGT at a constant flow rate of acetylene of 4 LPM under different loading conditions with different blend fraction of n-butanol/diesel as pilot fuel. Finally, the obtained results were analysed and a comparative study with neat diesel has been discussed below.

#### 3.2.1. Brake thermal efficiency

Fig. 7 demonstrates the deviation of BTE with altering BMEP for different blend ratio of n-butanol and neat diesel while inducting acetylene at a constant flow rate of 4 LPM in modified CI engine. It was observed that BTE for acetylene fuelled normal diesel engine varies from 3% to 29% from no load to full load however, it is lower than that of baseline diesel (4%–30%) the reason might be due to rapid combustion caused by higher flame velocity of acetylene. Furthermore when the n-butanol-diesel blend is used as pilot fuel combustion improves gradually, this might be due to a sufficient amount of oxygen available for proper igniting of acetylene air mixture eventually increasing the BTE. For B05 blend acetylene engine, BTE differs from 3% at zero loads to 31% at peak load meanwhile when the n-butanol percentage is increased to B10, BTE varies from 4% to 32% for no load to full loading conditions. For both cases (B05 and B10) blend obtained BTE is higher than normal diesel at peak loading conditions. Overall, the BTE of B10 blend fuelled acetylene engine is more than all tested fuels due to improved combustion. Similar outcomes have been stated in different literature (Srivastava et al., 2017; Behera et al., 2014; Lakshmanan and Nagarajan, 2011a; Behera and Murugan, 2013; Lakshmanan and Nagarajan, 2010a; Rakopoulos et al., 2011, 2010b; Yao et al., 2010). In general, it can be inferred that when n-butanol is added to neat diesel efficient and stable combustion takes place which eventually leads to better utilization of acetylene fuel.

#### 3.2.2. Exhaust gas temperature

Fig. 8 shows the distinction of the EGT with the change in BMEP. The EGT decreases with the induction of acetylene in comparison to normal diesel mode; this might be due to the higher flame speed of acetylene causing higher HRR eventually increasing heat transfer losses from the cylinder wall to the surroundings. This result is also verified by cylinder pressure graph mentioned above during combustion analysis. The EGT for a diesel engine operating

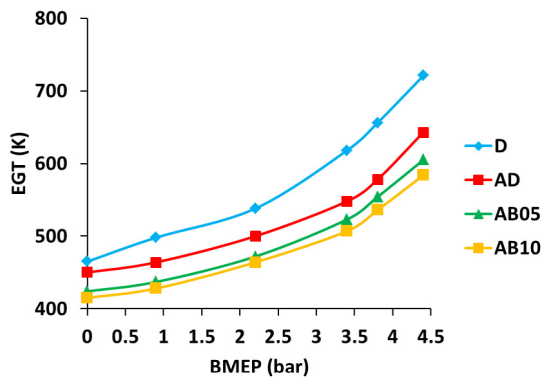


Fig. 8. Variation of exhaust gas temperature with BMEP.

for entire load range is higher than all tested fuels and it varies from 470 K to 721 K from no load to full load conditions, however, when acetylene is inducted at 4 LPM with diesel as pilot fuel the range differs from 450 K at zero loads to 643 K at high load. At maximum load, the EGT increases up to 605 K for B05 blend and 584 K for B10 blend while inducting acetylene in DFE. The EGT temperature rises with an increase in loads for all the cases. Similar results have been quoted in different literatures (Behera et al., 2014; Lakshmanan and Nagarajan, 2011a; Behera and Murugan, 2013; Lakshmanan and Nagarajan, 2010a; Rakopoulos et al., 2011, 2010b; Yao et al., 2010).

### 3.2.3. Brake specific energy consumption

The difference of BSEC with altering BMEP for different tested fuels is depicted in Fig. 9. In the beginning, when the acetylene is inducted, BSEC is observed to be higher at lower loading conditions in comparison to neat diesel but when the load is increased gradually BSEC reduces for acetylene dual-fuelled engine this may be due to improved combustion characteristics at the higher loads. For normal diesel engine, BSEC reduces from 2.3 kg/kWh at zero loads to 0.29 kg/kWh at high load. Similarly, while injecting neat diesel during acetylene fuelled CI engine BSEC reduces from 2.6 kg/kWh to 0.31 kg/kWh at zero loads to full load condition. Moreover, when B05 blend was used as pilot fuel in acetylene DFE the BSEC changes from 2.4 kg/kWh to 0.3 kg/kWh at zero loads to peak load. Further, when the B10 blend is injected as an ignition source in DFE, BSEC decreases from 2.5 kg/kWh for no-load to 0.3 kg/kWh at full load. It can be concluded that by increasing the n-butanol fraction in DFE the BSEC decreases and is similar to a normal diesel engine at medium to high loading conditions, this might be due to efficient combustion of gaseous fuel caused by sufficient quantity of oxygen supplied by n-butanol/diesel blend. Similar results have been mentioned in different literatures (Behera et al., 2014; Lakshmanan and Nagarajan, 2011a; Behera and Murugan, 2013; Lakshmanan and Nagarajan, 2010a; Rakopoulos et al., 2011, 2010b; Yao et al., 2010).

### 3.3. Emission parameters

IC engines produce undesirable pollutions during the burning of fuel. Some of the harmful emissions are expelled out in the environment when they remain un-burnt. The emissions results for acetylene fuelled CI engine while injecting different pilot fuels are compared with neat diesel.

#### 3.3.1. Carbon monoxide

The deviation of Carbon monoxide (CO) with the change in BMEP is depicted in Fig. 10. Most of the scientists have quoted the major reasons for CO formations are incomplete combustion

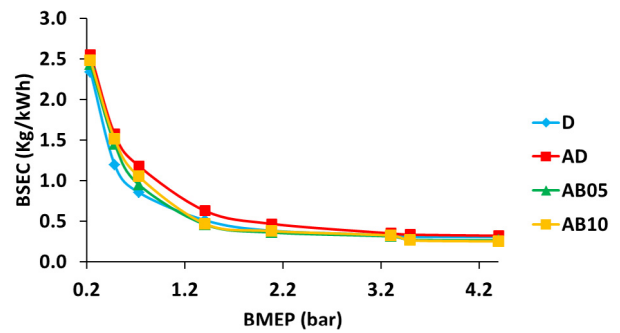


Fig. 9. Variation of BSEC with BMEP.

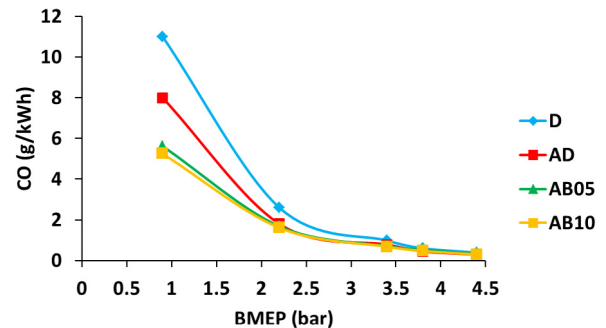


Fig. 10. Variation of CO emissions with BMEP.

caused due to lack of sufficient quantity of oxygen responsible for proper combustion. In all the cases, CO emissions are higher at no load condition whereas when the load is increased gradually CO formation reduces drastically this may be due to lean mixture formation at higher loads. For neat diesel operation CO varies from 11 g/kWh at no load to 0.39 g/kWh at peak loads whereas when acetylene is inducted at 4 LPM in DFE mode CO increases initially at no load, this might be because of the higher flame velocity of acetylene as well as poor atomization of pilot fuel leading to abrupt combustion. At full load, CO reduces to 0.30 g/kWh during acetylene induction while injecting diesel as pilot fuel. Furthermore while injecting B05 blend as a pilot fuel in DFE, CO declines to 0.32 g/kWh and for B10 blend acetylene DFE it decreases to 0.30 g/kWh relative to petroleum diesel. Hence, it can be clearly seen from Fig. 10 the lowest CO emissions were observed while utilizing B10 blend as a pilot fuel at full load in DFE compared to normal diesel. This may attribute to enough oxygen is available to combust acetylene air mixture while using the n-butanol blend in DFE. Similar outcomes have been reported in the literature (Srivastava et al., 2017; Behera et al., 2014; Lakshmanan and Nagarajan, 2011a; Behera and Murugan, 2013; Lakshmanan and Nagarajan, 2010a; Rakopoulos et al., 2011, 2010b; Yao et al., 2010).

#### 3.3.2. Hydrocarbons

The deviation of HC emissions versus BMEP is depicted in Fig. 11. The HC emission fluctuates from 0.32 g/kWh at no load to 0.07 g/kWh at peak load when the engine is operated on neat diesel whereas when acetylene is inducted, initially HC emissions rises due to heterogeneous fuel-air mixture formation due to excess amount of gaseous fuel being inducted at lower loads whereas when the load increases gradually gas-air mixture tends to be more homogeneous as well as lean mixture allows an adequate amount of oxygen to take part in the combustion phenomena which eventually enhances the performance of the engine at higher loads. When acetylene is inducted at full load



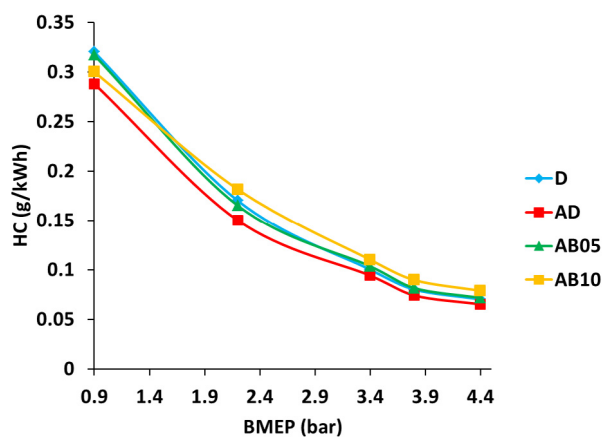


Fig. 11. Variation of HC emissions with BMEP.

the HC emissions reduces to 0.064 g/kWh while injecting neat diesel as pilot fuel moreover when n-butanol/diesel blend was injected as pilot fuel the level of HC emissions rises marginally in comparison to normal diesel i.e. 0.071 g/kWh for B05 blend further increasing n-butanol proportion to 10% in blend CO increased to 0.076 g/kWh which is relatively higher than petroleum diesel, this attributes to the joint effects of low cetane index and high evaporation heat of n-butanol/diesel blends. Lower cetane index of the blends lengthens the ID, permitting sufficient time for pilot fuel to evaporate meanwhile higher LHV the rate of evaporation, which causes increased HC emissions. Hence, it can be inferred that when the n-butanol percentage is increased in the acetylene fuelled CI engine HC emission inclines. Similar observations were perceived in various pieces of literature (Zhang and Balasubramanian, 2014; Rakopoulos et al., 2011, 2010b; Yao et al., 2010).

### 3.3.3. Oxides of nitrogen

$\text{NO}_x$  emissions are caused when a very high temperature of the combustion chamber is attained. Moreover,  $\text{NO}_x$  formation also depends on in-cylinder pressure and the equivalence ratio. Fig. 12 depicts the deviation of  $\text{NO}_x$  with a change in BMEP. For normal diesel,  $\text{NO}_x$  differs from 2.79 g/kWh at zero loads to 12.21 g/kWh at full load. Furthermore, when acetylene is inducted at 4 LPM the value of  $\text{NO}_x$  at maximum load for diesel pilot fuel is 15.13 g/kWh meanwhile when B05 and B10 blends were used as pilot fuel in acetylene fuelled diesel engine  $\text{NO}_x$  increases to 10.87 g/kWh and 10 g/kWh respectively at full load. It can be clearly seen from Fig. 12 rate of  $\text{NO}_x$  emissions declines for n-butanol/diesel acetylene fuelled CI engine; this might be due to the higher LHV, reduced flame temperature and decreased the heating value of n-butanol in comparison to normal diesel. Similar results were quantified by different researchers (Srivastava et al., 2017; Behera et al., 2014; Lakshmanan and Nagarajan, 2011a; Behera and Murugan, 2013; Lakshmanan and Nagarajan, 2010a; Rakopoulos et al., 2011, 2010b; Yao et al., 2010).

### 3.3.4. Smoke opacity

Fig. 13 depicts smoke opacity versus BMEP of different tested fuels. Many scientists have described the major reasons for smoke formations are deficient of oxygen molecules during combustion phenomena. It was found that smoke emissions decrease considerably for acetylene fuelled CI engine i.e. 24.2% lesser than baseline diesel at full load. Moreover when n-butanol was added to neat diesel smoke gets reduced drastically because of sufficient amount of oxygen was available for stable and efficient

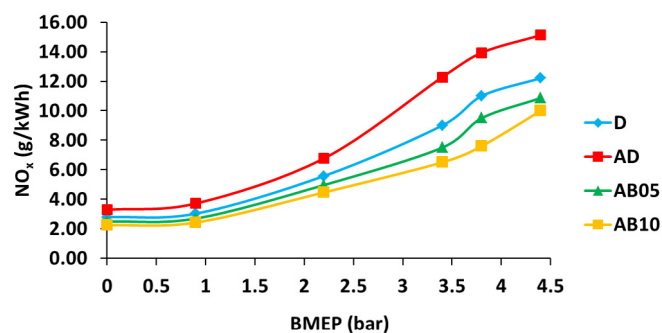


Fig. 12. Variation of  $\text{NO}_x$  emissions with BMEP.

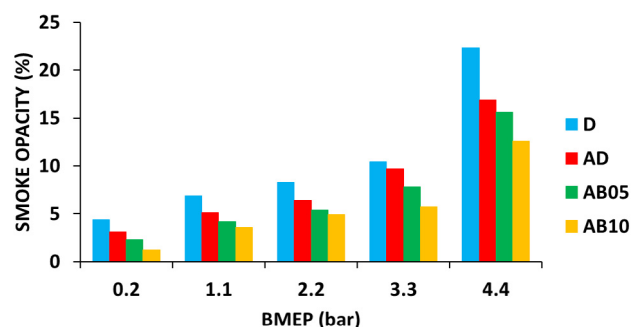


Fig. 13. Variation of smoke opacity with BMEP.

combustion of the acetylene fuel mixture. Overall, smoke opacity is lowest for B10 blend i.e. 44% lesser than normal diesel at maximum load. This might be because of the less number of carbon atoms present in n-butanol compared to petroleum diesel. Similar results were detected in many kinds of literature (Srivastava et al., 2017; Behera et al., 2014; Lakshmanan and Nagarajan, 2011a; Behera and Murugan, 2013; Lakshmanan and Nagarajan, 2010a; Campos-Fernández et al., 2012; Zhang and Balasubramanian, 2014; Rakopoulos et al., 2011, 2010b; Yao et al., 2010).

The graphs above show the comparative study between the normal diesel engine and acetylene DFE with different pilot fuels. In the current research analysis, the optimized blend ratio of n-butanol/diesel was investigated while inducting acetylene at 4 LPM flow rate during DFC. For optimizing the blend ratio of n-butanol and diesel in acetylene engine the combustion, performance and emission parameters were analysed. The experimentation was done by modifying a conventional diesel engine with minor changes. Similar results have been mentioned in different literatures (Behera et al., 2014; Lakshmanan and Nagarajan, 2011a; Behera and Murugan, 2013; Lakshmanan and Nagarajan, 2010a; Rakopoulos et al., 2011, 2010b; Yao et al., 2010).

On the basis of obtained results following conclusions were drawn:

## 4. Conclusions and future scope

### 4.1. Conclusions

- The maximum peak cylinder pressure was 77.87 bar among all tested fuels when B10 blend was injected as pilot fuel in acetylene DFE.
- The BTE is increased with an increased-butanol percentage in the blend. The maximum value of BTE for acetylene fuelled CI engine is 32% while injecting B10 blends as a pilot fuel which is better than all tested fuels.

- The consumption of diesel fuel is reduced by 32% at full load while operating B10 acetylene fuelled CI engine, which also proves maximum utilization of acetylene fuel takes place during B10 as a pilot fuel in acetylene DFE

- The CO values increase initially with acetylene induction compared to baseline diesel operation. But CO gradually decreases at high loads due to improved combustion at peak loads, the lowest value of CO emission is found for B10 blend while injecting as pilot fuel in acetylene DFE i.e. 0.30 g/kWh at full load which is very much lesser than the neat diesel engine.

- The HC values increase with increasing n-butanol percentage in blend during acetylene DFE and reached to 0.076 g/kWh at maximum load.

- The major issues of DFE are NO<sub>x</sub> formations, which are reduced while injecting B10 blend in acetylene DFE. The lowest value of NO<sub>x</sub> emission is 10 g/kWh at full load for B10 blend which is considerably lesser than all tested fuels.

Based on the experimental observations, 10% of n-butanol can be mixed with neat diesel to use as pilot fuel in acetylene fuelled CI engine for optimum performance under controlled emissions.

#### 4.2. Future scope

Recently, the utilization of acetylene as a biofuel has been more or less restricted to welding of machinery applications. Hence there is a huge opportunity for those vendors who can produce acetylene gas and provide some filling stations in the near future. Therefore, the author feels the obtained results will have significant importance for engine designers and researchers in the development and modification of the IC engine. A similar study can be done for multi-cylinder water-cooled CI engine. The research can be carried further with two different gaseous fuels simultaneously inducted in CI engine. The mixing properties of gaseous fuel with n-butanol can be further verified by using computer simulation software. Modern optimization techniques like ANN technique and the genetic algorithm can be used for finding the suitable blend proportion for diesel and higher-order alcohols. Electronic-based injection systems can be used to get an optimized result and to enhance the performance of the CI engine. Two different alcohols can also be used in DFE for better performance and emission characteristics. Overall still ample of research is required to get optimized production of renewable fuels such as acetylene as well as n-butanol as an alternative means of energy for sustainable development.

#### Appendix

$$\frac{dQ}{d\theta} = \frac{\gamma}{\gamma - 1} P \frac{dV}{d\theta} + V \frac{1}{\gamma - 1} \frac{dP}{d\theta}$$

where  $\theta$  is the crank angle in degrees and  $\gamma$  is the ratio of specific heat of the fuel and air.

$$\text{Input Fuel Energy } (Q_{f,in}) = \dot{m}_d CV_d + \dot{m}_{ace} CV_{ace}$$

$$\text{Work output } (W_{net}) = \frac{VI}{\eta_g \times 1000}$$

$$\text{Air Fuel Ratio (AF)} = \frac{\dot{m}_a}{\dot{m}_d + \dot{m}_{ace}}$$

$$\text{Diesel Substitution (\%)} = \frac{\dot{m}_D - \dot{m}_{PF}}{\dot{m}_D} \times 100$$

$$\text{Energy Share of Acetylene (\%)} = \frac{\dot{m}_{ace}}{\dot{m}_{ace} + \dot{m}_d} \times 100$$

$$\text{Brake Thermal Efficiency of Dual Fuel Engine } (\eta_{df} \%) = \frac{BP}{\dot{m}_{ace} CV_{ace} + \dot{m}_d CV_d}$$

$$\text{Brake Thermal Efficiency of Diesel Engine } (\eta_d \%) = \frac{BP}{\dot{m}_d CV_d}$$

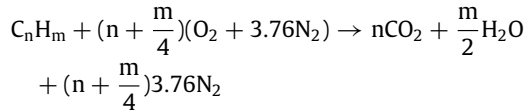
$$\text{Total diesel Consumption} = \frac{\dot{m}_d \times \rho \times 3600}{\text{time} \times 1000}$$

$$\text{Brake Specific Energy Consumption of normal Diesel (BSEC}_d)$$

$$= \frac{\dot{m}_d}{BP}$$

$$\text{Brake Specific Energy Consumption of Dual Fuel Engine (BSEC}_{df})$$

$$= \frac{\dot{m}_d + \dot{m}_{ace}}{BP}$$



#### Abbreviations

BMEP	Brake Mean Effective Pressure
BP	Brake Power
BTE	Brake Thermal Efficiency
BSEC	Brake Specific Energy Consumption
CA	Crank Angle
CI	Compression-Ignition
CO	Carbon mono oxide
CV	Calorific Value
DFC	Dual Fuel Combustion
DFE	Dual Fuel Engine
DI	Direct Injection
EGT	Exhaust Gas Temperature
HC	Hydrocarbon
HCCI	Homogeneous Charge Compression Ignition
IC	Internal Combustion
ID	Ignition Delay
LHV	Latent Heat of Vaporization
LPM	Litres Per Minute
NO <sub>x</sub>	Oxides of Nitrogen
SOI	Start of Ignition

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