Fuel 214 (2018) 489–496

Contents lists available at ScienceDirect

Fuel

journal homepage: www.elsevier.com/locate/fuel

# Effect of compression ratio on combustion and emission characteristics of C.I. Engine operated with acetylene in conjunction with diesel fuel

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ARTICLE INFO

*Keywords:*
Acetylene
Dual fuel mode
Compression ratio
Combustion
Emission

ABSTRACT

Predicted scarcity of conventional fuels and their increasing cost have given rise to interest in alternative fuels like biofuels, ethyl alcohol, methyl alcohol, hydrogen, producer gas, acetylene etc. in order to meet the energy requirement. Gaseous fuels are good for clean burning, but are costly. In the present study, a single cylinder, four strokes, direct injection, vertical, water cooled, variable compression ratio, multi fuel engine was used to operate in dual fuel mode. In this experiment acetylene was inducted at a flow rate of 7 lpm at various compression ratios of 18:1, 18.5:1, 19:1 and 19.5:1. Results were evaluated and compared on the basis of combustion, performance and emission parameters. Peak cylinder pressure and brake thermal efficiency are found to increase whereas exhaust gas temperature decreases with increase in compression ratio. The brake thermal efficiency was found to be maximum (21.18%) at 19.5:1 compression ratio.

## 1. Introduction

Increasing industrialization, growing energy demands, limited reserves of fossil fuel and increasing environmental pollution motivate researchers to explore and investigate possible alternatives of conventional petroleum fuels. Thermodynamic tests based on engine performance evolution have established the feasibility of using a variety of alternative fuels such as compressed natural gas (CNG), liquefied petroleum gas (LPG), acetylene, ethanol, methanol, biodiesel, vegetable oil and supplementary biomass sources in internal combustion engines. Dual-fuel mode operation has been used as one of the prominent methods of conserving the conventional fuels such as diesel and petrol [1]. Gaseous fuels are top suited for IC engines since physical impediment is negligible. There are many gaseous fuels that may be used as nonconventional fuel. However, gaseous fuel, when supplied via intake air manifold, displaces equivalent amount of air and leads to poorer volumetric efficiency of the engine.

Wulff et al. [2] first proposed use of a mixture of acetylene and alcohol (ethanol, methanol) to a spark ignition (SI) engine and also in a compression ignition (CI) engine in dual fuel mode in a controlled way. It exhibited higher efficiency than conventional engines along with cleaner burning. The combustion process had lower temperature, which potentially prolonged the expected life of the engine. Further, they studied the behavior of diesel at various power conditions and speeds by introducing acetylene as primary fuel and diesel as secondary fuel in dual fuel mode at various power outputs and various speeds. Positive results were reported like reduction in $NO_x$, HC and CO emissions compared to that of baseline diesel fuel combustion [3].

Sharma et al. [4] demonstrated use of acetylene as an alternative fuel in IC engine. They performed experiments on SI engine taking acetylene as primary fuel and ethanol as secondary fuel in order to reduce the combustion chamber temperature. They reported acetylene as a good fuel for SI engine in dual fuel operation mode, the amount of $CO_2$ emitted is also minimized. Soni et al. [5] explained fabrication of dual fuel engine and reported some shortcomings in the use acetylene as a secondary fuel in SI engine. Brusca et al. [6] analyzed SI engine running on alcohol (ethanol) and acetylene. The intake system of engine was modified and two electronically controlled injectors (one for acetylene and other for alcohol) were used. Acetylene alcohol combination was reported as a good alternative to contemporary engine fuels in terms of engine performance as well as emission parameters.

Lakshmanan and Nagarajan [7], performed experiments on acetylene-aspirated diesel engine to analyze performance and emission parameters in dual fuel mode. In dual fuel mode of CI engine, acetylene is inducted as a secondary gaseous fuel with diesel as an injected pilot fuel. In their first experiment, a fixed quantity (3 lpm) of acetylene was aspirated to determine performance and emission parameters of a single cylinder direct injection engine. They concluded that, for full load operation, the brake thermal efficiency (BTE) in dual fuel mode is lesser than neat diesel operation. An appreciable reduction is reported in

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https://doi.org/10.1016/j.fuel.2017.11.051
Received 5 August 2015; Received in revised form 16 June 2017; Accepted 16 November 2017

emission level of HC, CO, $CO_2$ and smoke density. Dual fuel operation shows a reduction in exhaust gas temperature (EGT) and increase in peak cylinder pressure. In another study [8], they inducted acetylene using timed manifold injection technique (TMI) for various flow rates of 110 g/s, 180 g/s and 240 g/s and recommended an optimized injection timing of 10° after top dead center (ATDC) and at 90° crank angle (CA) by using an electronic control unit. A slight increase in BTE is observed for all corresponding gas flow rates at rated power. Emission parameters show similar trends as in the previous study. Further, they conducted experiments for different flowrates of acetylene (0.20 kg/h, 0.26 kg/h and 0.39 kg/h) [9]. It is concluded that BTE in the dual fuel mode is lower by about 3.5% for 0.39 kg/h of acetylene flow rate at full load compared to single fuel diesel operation. $NO_x$ emission and Smoke density also increases with increase in acetylene flow rates. Decrease in HC, CO and $CO_2$ are observed for acetylene operated dual fuel mode. Later they investigated [10] port injection of acetylene in direct injection (DI) diesel engine in dual fuel mode. They concluded that it is possible to run a DI diesel engine with stable combustion using acetylene as a fuel and diesel as a source of ignition for a range of acetylene flow rates from 110 g/h to 240 g/h without knocking. It is also observed that BTE obtained is similar to diesel operation at full load. Further, NOx emission decreases while emission of HC, CO, $CO_2$ and smoke level increases when compared to neat diesel operation. They also later studied [11] the combustion and emission parameters of acetylene in dual fuel mode using TMI with exhaust gas recirculation (EGR) for further reduction of $NO_x$ emissions.

Sudhesh and Mallikarjuna [12] studied the effects of conventional and reverse cooling of water flow directions on the performance of an acetylene fueled single cylinder homogeneous charge compression ignition (HCCI) engine. They demonstrated that reverse flow direction of cooling water exhibits an increment in BTE and reduction in external intake charge heating at various load conditions in dual fuel mode compared to conventional direction of flow. HC and CO emissions are higher for both directions of cooling water flow in HCCI mode. Further, they developed strategy for EGR of acetylene fueled HCCI engine to obtain best inlet charge temperature [13]. They concluded that BTE of acetylene HCCI mode is comparable to the conventional operation of the engine. There was a reduction in $NO_x$ and increment in HC, CO emissions with EGR. By the use of hot EGR and cold EGR in proper proportion, stable combustion phasing obtained.

Kumaran et al. tried a novel bio based Tri-fuel combination for CI engine [14]. They used diesel and turpentine blend (40% turpentine and 60% diesel) as primary fuel and acetylene as secondary gaseous fuel. The tri-fuel concept was observed to increase BTE by 1–3% over conventional fuel. Emission level of HC, CO, $CO_2$ and exhaust gas temperature (EGT) are found comparatively lower than single fuel diesel operation. Behera et al. [15] conducted experiments, employing used transformer oil (UTO) with acetylene introduced at four different flow rates viz 132 g/h, 198 g/h, 264 g/h and 330 g/h along with air in dual fuel mode. Results were compared with diesel acetylene dual fuel mode for the same engine. $NO_x$, smoke density and EGT are reported to be high in UTO-acetylene dual fuel compared to diesel-acetylene dual fuel. Ignition delay is found shorter in UTO-acetylene dual fuel mode.

Mahla et al. [16] studied the performance parameters of CI engine in dual fuel mode. A fixed quantity of acetylene (12 lpm) and diethyl ether blend with diesel (DEE10, DEE20, DEE30) were used as combustion source. Experimental results show that the brake power and BTE increases with addition of diethyl ether up to 20% without sacrificing the brake specific fuel consumption while beyond this percentage, the performance drops and engine starts knocking. EGT is lower in dual fuel mode than neat diesel operation. Nathan et al. [16], investigated the effects of charge temperature and EGR on the combustion and emission characteristics of acetylene fueled HCCI engine. In their experiment, they took heated intake air at various temperatures in order to obtain better thermal efficiency and optimized EGR operation. It was demonstrated that at high brake mean effective pressure (BMEP), hot EGR starts knocking, so proper control is needed over the temperature and amount of EGR.

Choudhary and Nayyar studied optimization of induction flow rate of acetylene in DI engine in dual fuel mode [17]. They demonstrated that among the four flow rates (5 lpm, 6 lpm, 7 lpm and 8 lpm), 7 lpm is most suitable for dual fuel operation. It is observed that the peak cylinder pressure increases with increase in flow rate of acetylene induction up to a certain limit and then starts decreasing. Heat release rate is observed to increase with an increase in quantity of acetylene induction and is found generally higher compared to neat diesel operation. Level of CO emission decreases while $NO_x$ increases in dual fuel mode.

Bora et al. [18] observed that a particular fuel has unique chemical and physical properties. The combustion characteristics changes with fuel properties, therefore the operating parameters of the same need to be adjusted. Compression ratio is one of the important parameters that affect the engine performance.

From literature, it is evident that acetylene has been perceived as promising fuel in both S.I. and C.I. engines in dual fuel mode however, there are limited study published on compression ratio in dual fuel mode of operation for C.I. engine. In order to obtain optimum performance of the engine, a detailed investigation is necessary to identify the behavior of combustion, performance and emission parameters at various compression ratios.

In this paper, effect of compression ratio on combustion parameters are investigated. Conventional performance parameter such as brake thermal efficiency, exhaust gas temperature, brake specific energy consumption and volumetric efficiency are studied at various load conditions. Furthermore, emission parameters are also examined at those load conditions for the various compression ratios for dual fuel mode operation.

## 2. Experimental setup and procedure

A single cylinder, direct injection, four strokes, vertical, water cooled engine is selected, the specification of which is given in the Table 1. Fig. 1 illustrates the experimental setup. An acetylene connection is made at the intake air manifold of the engine. Diesel flow is

**Table 1**
Test engine specifications.

| Description | Specifications |
|---|---|
| Type | Single cylinder, direct injection, four-stroke, vertical, water-cooled, naturally aspirated variable compression ratio multi-fuel diesel engine |
| Power | 3–5 HP |
| Rated speed | 1450–1600 rev/min (Governed Speed) |
| Number of cylinders | One |
| Bore | 80 mm |
| Stroke | 110 mm |
| Injector pressure | 203 bar |
| Injection timing by spill | 23° CA BTDC |
| Method of loading | Eddy Current Dynamometer |
| Method of starting | Manual Crank Start |
| Method of cooling | Water cooled |
| Overall dimensions | 1400 × 1300 × 1100 mm |
| Weight | 225 kg |
| Air tank size (mm) | 400 × 400 × 400 mm |
| Orifice size (mm) | 20 mm |
| Valve timings | |
| Inlet valve opens | 4.5° CA BTDC |
| Inlet valve closes | 35.5° CA ABDC |
| Exhaust valve opens | 35.5° CA BTDC |
| Exhaust valve closes | 4.5° CA ATDC |

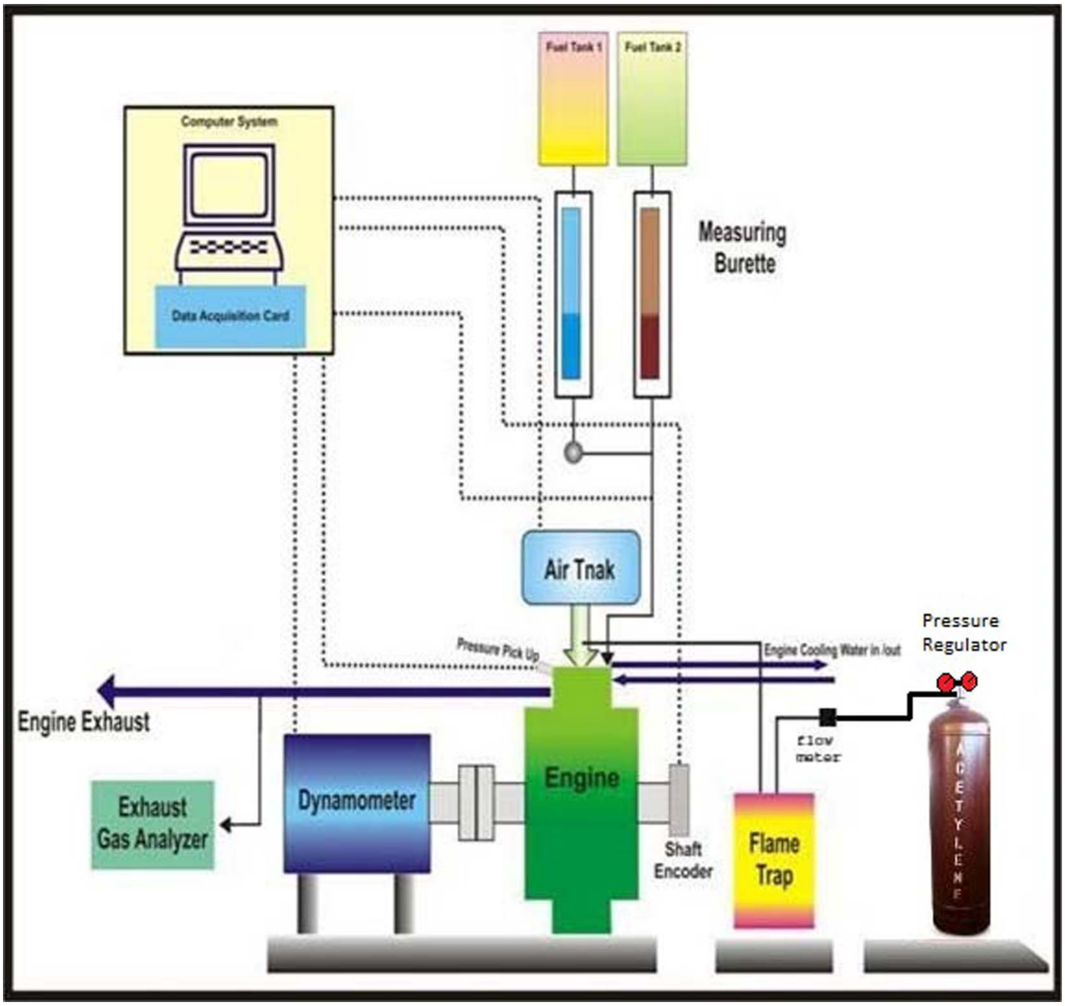


**Fig. 1.** Schematic of experimental Setup.

**Fig. 2.** Photographic view of test engine.

governed by the governor and the acetylene flow rate is varied manually with the help of gas flow meter. Acetylene gas is continuously inducted at fixed flow rate of 7 lpm. The compression ratio of the engine is varied by raising and lowering the bore and the head of the engine. A photographic view of test setup is given in the Fig. 2.

1 – Engine, 2 – Dynamometer, 3 – Diesel tank and Measurement system, 4 – Air Flow Surge tank and Meter, 5 – Air Pre-Heater, 6 – HC/CO Analyzer, 7 – PC Based Data Acquisition system, 8 – Charge Amplifier, 9 – Pressure Pickup, 10 – Shaft Position Encoder, 11 – Acetylene cylinder, 12 – Control valve, 13 – Pressure regulator, 14 – Gas Flow Meter, 15 – Flame Arrestor, 16 – Flame Trap, 17 – Control valve, 18 – Gas Mixer, 19 – Exhaust outlet, 20 – Air Inlet, 21 – Temperature and Pressure Measurement Points

Cylinder pressure signals, obtained from a flush mounted quartz pressure pickup are recorded on a computer system. The heat release rate and other combustion parameters are recorded using software developed to obtain the pressure signals for 100 successive engine cycles. The software calculates heat release rate on the basis of Ist law of thermodynamics using Eq. (i).

$$\frac{dQ_n}{d\theta} = \frac{\gamma}{\gamma-1}p\frac{dV}{d\theta} + \frac{1}{\gamma-1}V\frac{dp}{d\theta} \quad \text{(i)}$$

where $\frac{C_p}{C_v} = \gamma, R = C_p - C_v$

Emission parameters are recorded by using a five-gas exhaust analyzer (Airrex HG-540; Hephzibah Co. Ltd., Korea). A Non-dispersive infrared analyzer is used to measure concentrations of carbon dioxide and carbon monoxide. Electrochemical analyzer is used to measure hydrocarbons emissions and content of oxygen. NOx is measured by UV analyzer utilizing electrochemical method. Experiments are conducted from zero to full load of operation while engine speed is kept constant at 1550 rev/min. Load on the engine is adjustable and recorded with the help of a computer. The combustion, performance and emission parameters are calculated and compared for various compression ratios in dual fuel operation.

Formulas used for computing are Eqs. (ii) and (iii)

$$\eta = \frac{B.\,P.}{I.\,P.} \quad \text{(ii)}$$

$$(I.\,P.\,)_{Dualfuel} = (m_f * C.\,V.\,)_{diesel} + (m_f * C.\,V.\,)_{acetylene} \quad \text{(iii)}$$

where, B.P. = Brake Power, I.P. = Indicated Power, $M_f$ = Mass of fuel, C.V. = Calorific value of fuel.

Table 2 shows the instrument accuracy for the various measurements as given in the instrument manuals. The relevant properties of diesel and acetylene are summarized in Table 3.

## 3. Result and discussion

In the present work, acetylene gas is supplied through air intake manifold in C.I. engine with diesel being the ignition source. Several tests are carried out at different compression ratios to compare the performance of the engine on various parameters in dual fuel mode.

**Table 2**
Accuracy of measurements.

| Measurements | Accuracy |
|---|---|
| Load | ± 0.2% |
| Speed | ± 2 rev/min |
| Time | ± 0.5% |
| Temperatures | ± 1 °C |
| Pressure | ± 0.2 bars |
| NOX | ± 2 ppm |
| HC | ± 1 ppm |
| CO | ± 0.001% |
| Flow rate | ± 1% FS |

**Table 3**
Physical and combustion properties of acetylene and diesel. [9]

| Properties | Diesel | Acetylene |
|---|---|---|
| Composition | $C_{12}H_{26}$ | $C_2H_2$ |
| Density, kg/m3(At 1 atm & 20 °C) | 840 | 1.092 |
| Flammability limits (Volume%) | 0.6–5.5 | 2.5–8.1 |
| Auto ignition temperature (K) | 527 | 598 |
| Lower Calorific Value (kJ/kg) | 42500 | 48225 |
| Flame Speed (m/s) | 0.3 | 1.5 |
| Adiabatic Flame Temperature | 2200 | 2500 |
| Stoichiometeric air fuel ratio (kg/kg) | 14.5 | 13.2 |

### 3.1. Combustion parameters

#### 3.1.1. In-cylinder pressure crank angle diagram

Fig. 3 shows the variation of In-cylinder pressure with crank angle for different compression ratios. The peak cylinder pressure rises with increase in compression ratio. It is due to the fact that with increase in compression ratio, more quantity of the secondary fuel is available for combustion. Further, advancement in the peak cylinder pressure is also observed. This observed phenomenon of advancement in attaining peak pressure is expected due to instantaneous combustion of gaseous fuel in the cylinder at higher pressure [19]. Here instantaneous combustion means burning of part or whole of the pilot fuel that is diesel in addition to combustion of a small part of acetylene gas.

Another possible reason of higher peak in-cylinder pressure at higher compression ratio is that more oxygen along with fixed flow rate of acetylene gas mixture is inhaled at higher compression ratio. Peak pressure observed for compression ratio of 18:1 is 63.96 bar at 10.03 degrees after TDC, 63.61 bar at 9.66 degrees after TDC for compression ratio 18.5:1, 67.43 bar at 9.05 degrees after TDC for compression ratio 19:1 and 69.06 bar at 9.07 after TDC for compression ratio 19.5:1.

#### 3.1.2. Heat release rate

Fig. 4 shows variation of heat release rate with CA for dual fuel mode at various compression ratios. The combustion of acetylene takes place in four stages namely

- Pre-oxidation reaction of the gas (Ignition delay)
- Combustion of pilot fuel
- Premixed combustion phase
- Diffusion combustion phase

The highest heat release rate for dual fuel mode is observed 28.08 J/deg at a crank angle of 11.57 degrees after TDC at compression ratio 19.5:1. The heat release rates of 27.31 J/deg, 26.77 J/deg and 27.81 J/deg are obtained for compression ratios 19:1, 18.5:1, and 18:1 respectively, keeping other conditions constant.

#### 3.1.3. Mass fraction burnt

Mass fraction burnt (MFB) is known as a normalized quantity, which explains the combustion process of chemical energy as a function of crank angle (CA) on a scale of 0 to 1. It is determined on the basis of fuel burn rate [20]. The curves drawn between MFB and CA for dual fuel operation for various compression ratios at full load condition are shown in Fig. 5. It is observed that the duration of combustion for compression ratio 19.5:1 is shorter than other compression ratios tested at full load operation.

### 3.2. Performance parameters

In the context of IC Engine, performance means how effectively the engine provides energy conversion and how much work an engine is providing in relation to the supplied energy. A few standard performance parameters for dual fuel operation of engine are tabulated in

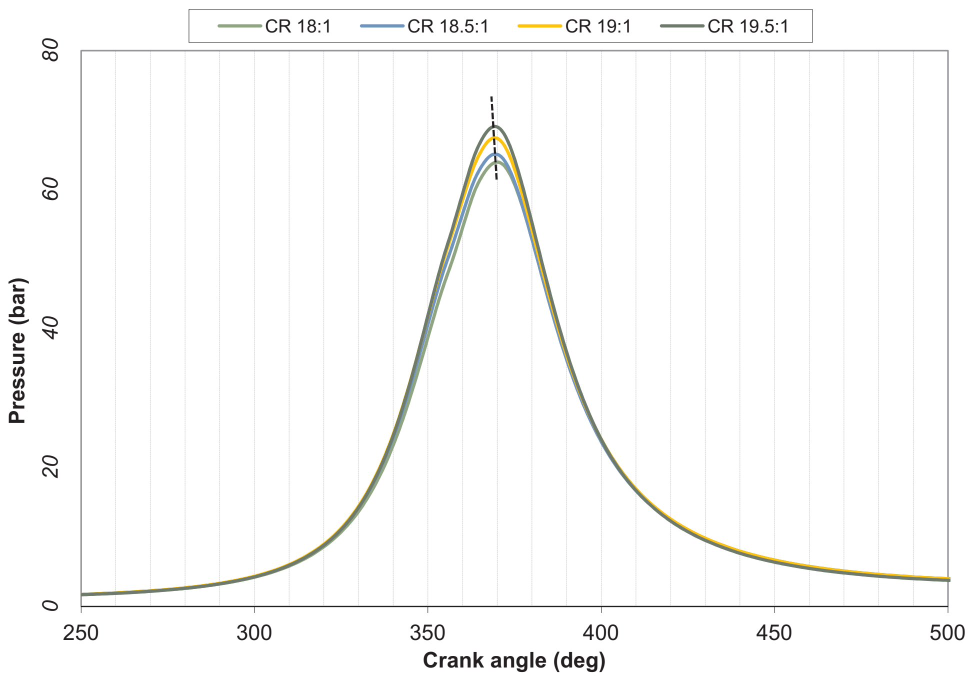


**Fig. 3.** Changes in Cylinder Pressure with Crank Angle.

Table 4. at full load condition.

*3.2.1. Brake thermal efficiency*

Brake thermal efficiency is computed from the ratio of brake power to the total heat supplied by the combustion of fuel. The curves shown in Fig. 6 are drawn between% load applied and BTE for dual fuel mode at various compression ratio. It is observed that increases in compression ratio lead to greater turning effect on crank. This results into more brake torque, so BTE increases as compression ratio increases. The highest brake thermal efficiency obtained is for 21.18% for acetylene induction at 7 lpm at compression ratio 19.5:1 in dual fuel operation.

*3.2.2. Exhaust gas temperature*

The curves drawn between exhaust gas temperatures with% load for dual fuel operation at various compression ratios are shown in Fig. 7. Results show that the exhaust gas temperature decreases with increase in compression ratio. Since expansion ratio in most of the cases is reverse than that of compression ratio, so that with an increase in compression ratio the expansion ratio also increases. The decrease in exhaust gas temperature with increase in compression ratio may be due to a greater expansion of burnt gases and greater work-done by burnt mixture. The exhaust gas temperatures observed at full load for dual mode are 638.58 °C, 632.99 °C, 612.03 °C and 581.95 °C for CR 18:1, 18.5:1, 19:1 and 19.5:1 respectively.

*3.2.3. Brake specific energy consumption*

Fig. 8 shows the variation of BSEC with applied% of load. Brake specific energy consumption (BSEC) decreases for overall operation with increase in compression ratio. It is due to the fact that with increase in compression ratio, the In-cylinder temperature also increases

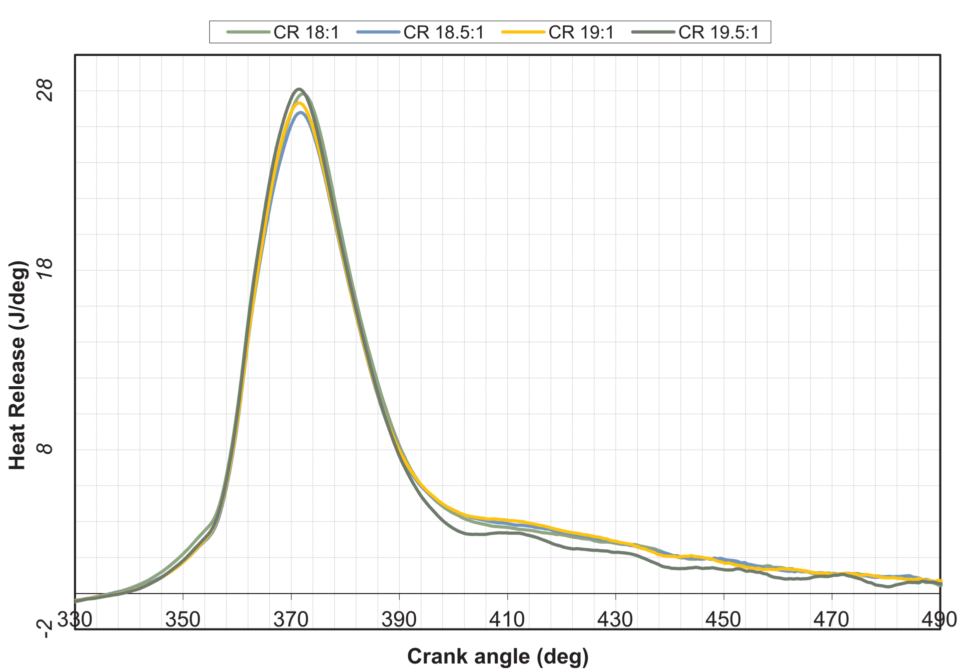


**Fig. 4.** Changes in Heat Release with Crank Angle.

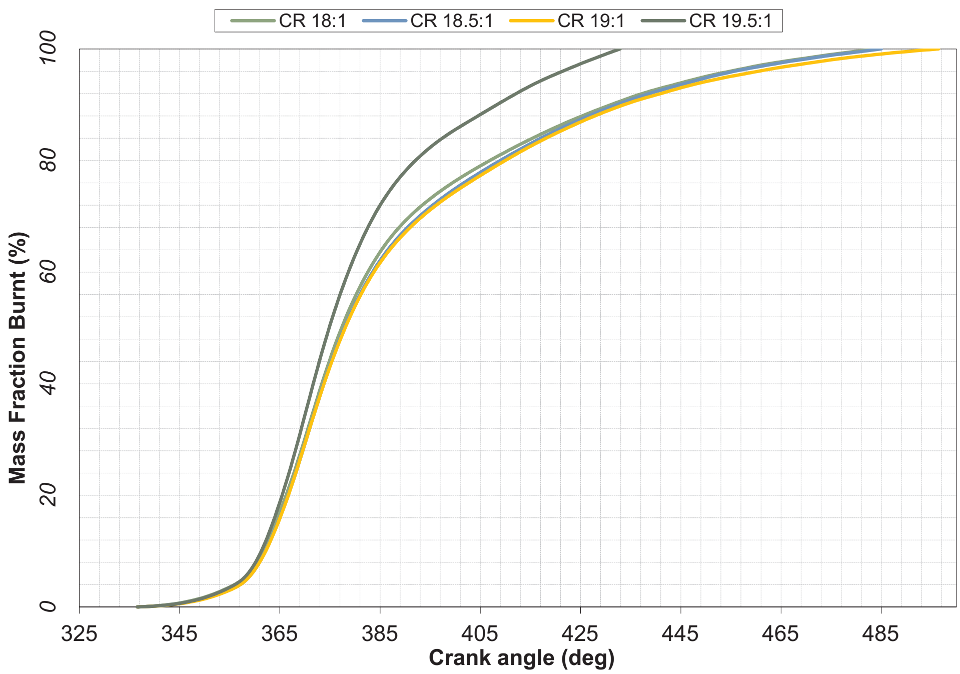


**Fig. 5.** Changes in MFB with Crank Angle.

**Table 4**
BTE, cylinder pressure, EGT and volumetric efficiency for acetylene induction of 7 lpm at full load operation for different compression ratios.

| Compression ratio | BTE (%) | Cylinder pressure (bar) | EGT (°C) | Volumetric efficiency (%) |
|---|---|---|---|---|
| 18:1 | 20.30 | 63.96 | 638 | 64.02 |
| 18.5:1 | 20.51 | 63.61 | 632 | 64.45 |
| 19:1 | 20.66 | 67.43 | 612 | 65.37 |
| 19.5:1 | 21.19 | 69.06 | 581 | 66.59 |

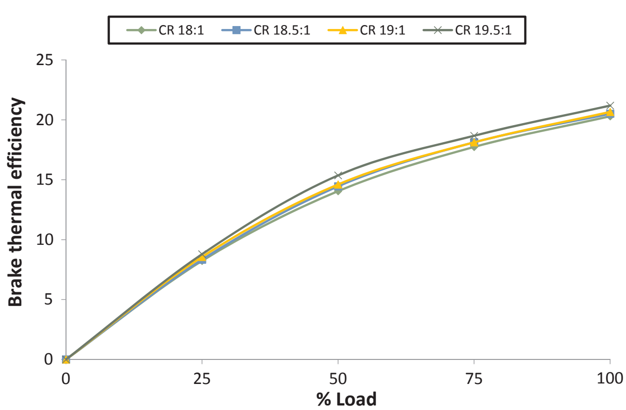


**Fig. 6.** Changes in Brake Thermal Efficiency with% load.

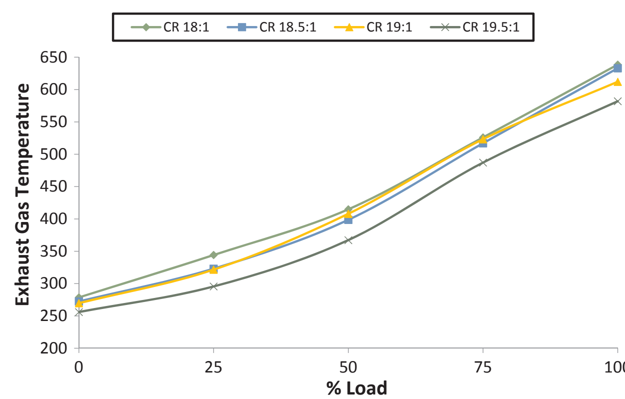


**Fig. 7.** Changes in Exhaust Gas Temperature with% load.

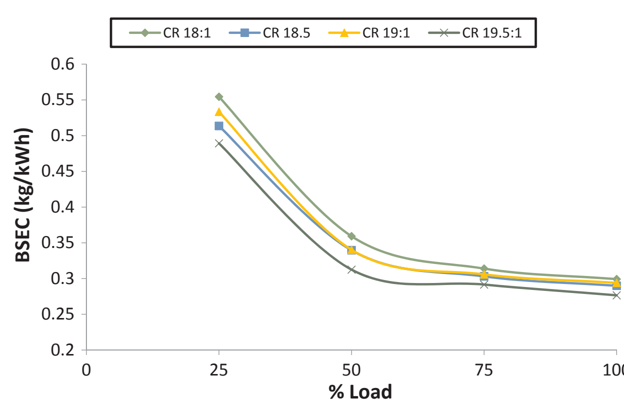


**Fig. 8.** Changes in BSEC with% load.

resulting into more efficient combustion of fuel and increase in brake power. BSEC trend show continuous decrement with increase in engine load. It can be ascribed to the fact that at higher load condition, higher brake power is required leading to low BSEC.

### 3.2.4. *Volumetric efficiency*

Volumetric efficiency indicates the breathing ability of the engine. The engine should be able to take in as much air as possible. The curves drawn between volumetric efficiency and% load in dual fuel mode for various compression ratios are shown in Fig. 9. Experimental results show that volumetric efficiency decreases with increase in engine load. This is because at higher loads, higher power is required which in turn increases the average temperature of combustion chamber and engine walls. The engine walls transfer heat to air intake system thereby reducing the air density and volumetric efficiency. Further, at higher compression ratio, the volumetric efficiency is also higher. This is due to the fact that with an increase in compression ratio, the intake capacity of engine also increases.

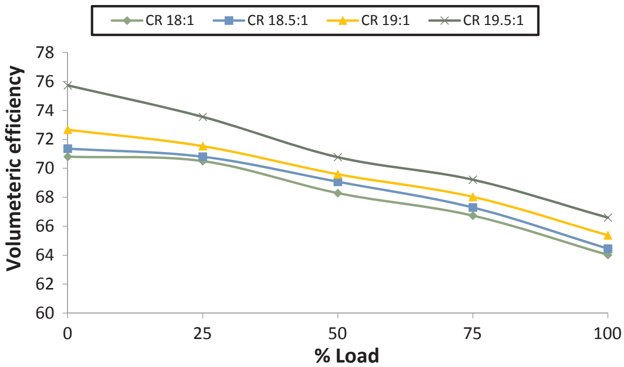


**Fig. 9.** Change in volumetric efficiency with% load.

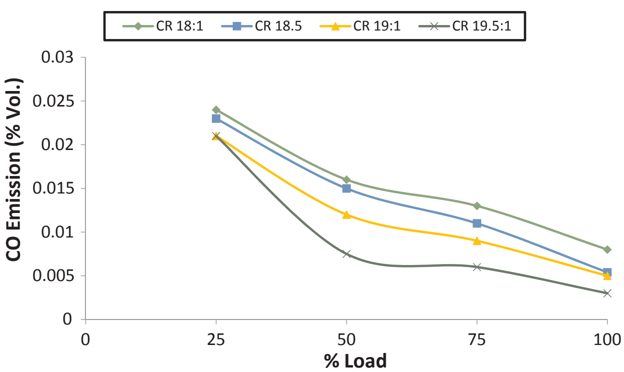


**Fig. 10.** Changes in CO with% load.

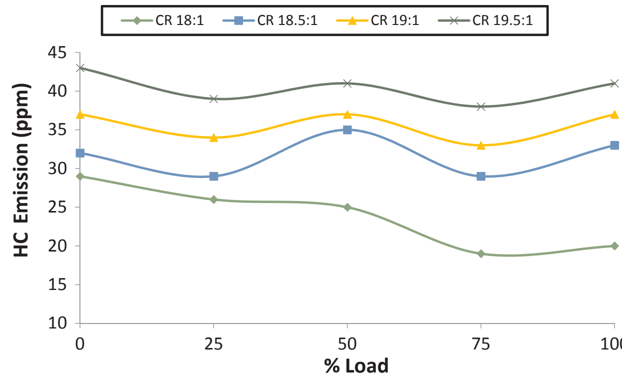


**Fig. 11.** Changes in HC with% load.

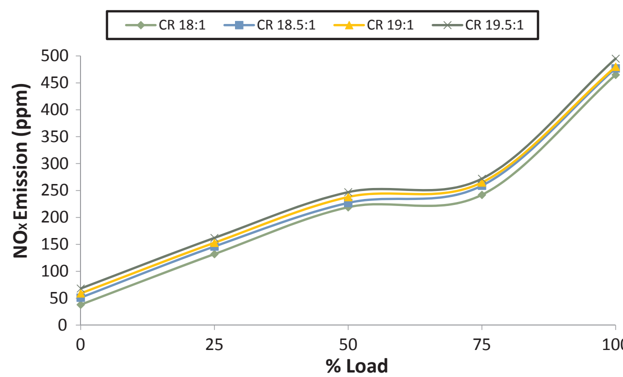


**Fig. 12.** Variation of $NO_x$ with% load.

### 3.3. *Emission parameters*

#### 3.3.1. *Carbon monoxide (CO)*

Lack of oxygen at high speed is the prime reason of CO formation. Combustion chamber temperature is also an important factor along with physical and chemical properties of fuel [21]. Fig. 10 shows the variation of CO emission with% load for different compression ratio. It is observed that with increase in compression ratio, CO emission decreases. This is because, with increase in compression ratio, more air and hence more oxygen is available inside the cylinder for complete combustion. It is observed that of compression ratio increases, the intake capacity of engine also increases. At higher compression ratios, more oxygen is available for combustion so there is less formation of CO at higher compression ratio.

#### 3.3.2. *Unburnt Hydrocarbon (UHC)*

UHC emissions result from incomplete combustion. Acetylene has flame speed of 1.5 m/s and flammability limits 2.5–8.1(% volume) whereas diesel has a flame speed of 0.3 m/s and flammability limits 0.6–5.5 (% volume) [10]. Thus, acetylene as fuel has higher burning velocity and wider ignition limits. It also helps to operate the engine leaner with higher energy release due to higher energy content. These characteristics leads to better combustion of the charge and that leads to decrease in UHC emissions. The UHC emission with% load at various compression ratios is plotted in Fig. 11. Experimental results also show that UHC increases with increase in compression ratio.

#### 3.3.3. *Oxides of Nitrogen ($NO_x$)*

Fig. 12 shows $NO_x$ emission with% load at different combustion ratios for dual fuel mode. According to Zeldovich mechanism model [22], NOx formation depends upon the reaction duration, the reaction temperature and also prominently upon availability of oxygen at higher temperature. In dual fuel mode, when acetylene is inducted, higher NOx formation is attributed to higher in-cylinder temperature because of faster energy release, owing to higher peak cylinder pressure [7]. Further, at higher compression ratio, the in-cylinder temperature is higher and lead to higher $NO_x$. The amount of $NO_x$ at full load operation for compression ratio 19.5:1 is about 495 ppm.

## 4. Conclusions

1. The peak cylinder pressure has a upward trend with increase in compression ratio for dual fuel operation. The maximum pressure is 69.06 bar for compression ratio 19.5:1.
2. The highest heat release rate for acetylene induction is 28.08 J/deg at crank angle 11.57 degrees after TDC for compression ratio 19.5:1.
3. The combustion duration is less as in the case of high compression ratio 19.5:1, compared to operation at other compression ratios.
4. The brake thermal efficiency increases with increase in compression ratio due to better combustion. The brake thermal efficiency obtained is 21.18% for acetylene induction of 7 lpm at compression ratio 19.5:1.
5. Exhaust gas temperature decreases with increase in compression ratio. The exhaust gas temperature at full load for dual fuel mode is found 581.95 °C for CR 19.5:1.
6. For CR 19.5:1 the volumetric efficiency is 66.59% of full load operation, which is the highest in the range.
7. UHC and $NO_x$ are found higher while CO emissions are found lower at full load for compression ratio 19.5:1.

## Aknowledgement

The authors wish to express their gratitude to all staff members of Mechanical Engineering Department of Govt. Engineering College, Bikaner and especially to Dr. Jaiprakash Bhamu for support.

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