Evaluation of Effects of Compression Ratio on Performance, Combustion, Emission, Noise and Vibration Characteristics of a VCR Diesel Engine

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Abstract- In this study, an experimental study has been evaluated on a variable compression ratio diesel engine to investigate the compression ratio effects on engine performance, combustion, emission, vibration, and noise characteristics. The result of engine characteristics were studied at 12:1, 14:1, and 16:1 compression ratios under partial load condition. Experimental engine was operated with diesel, biodiesel and diesel-biodiesel blends throughout the experiments. Experimental study indicated that compression ratio considerably affects the engine characteristics that measured in this study. It is observed that in the experiments, higher compression ratio results in higher brake thermal efficiency and thus lower specific fuel consumption. Higher compression ratios resulted with higher cylinder pressure and thus improved combustion. Increasing compression ratio improved carbon monoxide emission, however, increased carbon dioxide emission and nitrogen oxides formation. Also, noise and vibration of the engine reduced with the increment of compression ratio.

Keywords- Compression ratio, Performance, Emission, Noise, Vibration

1. Introduction

A significant quantity of energy is exerted all over the world perpetually and the major part of this energy is supplied by fossil fuels. But, there is a known fact that these sources are not renewable and in near future these sources will be exhausted. Therefore, the research studies for alternative sources which are renewable and sustainable energy have gained importance. Beside this hazard there are other concerns such as high price of crude petroleum and air pollution [1]. In recent studies, researches on the internal combustion engines (ICE) have been focused on alternate fuels [2]. Therefore, the effects of alternative fuels on engine parameters like injection timing, and compression ratio (CR) have been studied by many scientists. Many researchers have examined these parameters generally experimenting with a variable compression ratio engine (VCR). Effects of compression ratio, which can be defined as ratio of the largest volume to smallest ratio in the combustion chamber, on characteristics of performance and emissions have been investigated by many researchers [2-6].

Biodiesel is potential renewable and sustainable energy feedstock that is synthesised via transesterification reaction [5-11]. Biodiesel could be synthesised from many different feedstocks such as animal fats, vegetable oils and waste sources. Many scientists researched different raw materials for biodiesel production [12-15]. Edible or non-edible vegetable oils such as pomace oil [16], soybean oil [17], castor oil [18], tobacco seed oil [19], safflower seed oil [20], terebinth oil [21], tea seed oil [6] and karanja oil [22] etc. have been used as feedstock for synthesising biodiesel fuel.

Lately, study on vibration and noise characteristics of ICEs has gained significant importance [23-24]. How et al. (2014) fuelled the engine by coconut biodiesel to observe its effect on engine vibration, performance and emissions [25]. Taghizadeh-Alisaraei et al. (2012) also investigated vibration effect of biodiesel on four stroke six cylinders diesel engine [26]. Whereas Gravalos et al. (2013) worked with spark ignition engine. They fuelled it with unleaded gasoline, ethanol blends and methanol blends [27]. Torregrosa et al. fuelled their test engine with soybean and rapeseed biodiesel while Sanjid et al. (2014) used palm and jatropha biodiesel blends to analyse its noise and performance characteristic on diesel engine [28-29].

In this study, diesel fuel and biodiesels produced from crude false flax oil, sunflower oil, canola oil, and blends of these fuels with diesel fuel were used as test fuels to evaluate performance, emission, combustion, noise and vibration characteristics of a VCR engine. The prepared blends of conventional diesel and biodiesel were tested in a VCR engine with different CRs under partial load condition (60%). In experiments, performance characteristics of engine such as brake thermal efficiency (BTHE) and specific fuel consumption (SFC) were compared. The combustion characteristics of the test fuels with different CRs were investigated. Furthermore, emission, noise and vibration characteristics of the VCR engine were evaluated.

2. Material Method

The experimental tests of the study were evaluated in Çukurova University, laboratories of the Automotive Engineering Department.

2.1. Test Fuels

False flax (Camelina Sativa) oil, sunflower oil, and canola oil were used as feedstocks for biodiesel production. Methyl esters were synthesised by using transesterification method. Reactant and catalyst were methanol and sodium hydroxide (NaOH) in the reactions. To be able to provide best condition for production, transesterification reactions were performed in a reactor which is equipped with stirrer, thermometer, and condenser. Alcohol to oil molar ratio was 6:1 in the reactions. The reactions were done with 0,5% weight ratio sodium hydroxide and 20% volume ratio methanol according to oil weight and volume. To get sodium methoxide, sodium hydroxide and methanol were reacted. Then, sodium methoxide and oil samples were blended in the reactor. By stirring the mixture, they reacted for 90 minutes at 65 oC. With the end of the reaction, the crude samples were waited in a funnel for 8 hours for separation. And then, methyl ester and crude glycerine was separated. At the next step, until the crude methyl ester became clear, it was washed with warm water. To evaporate the water, washed crude methyl ester was dried at 110 oC for 1 hour. Finally the crude methyl esters were passed through a filter in order to obtain clean false flax methyl ester (FME), sunflower methyl ester (SME) and canola methyl ester (CME). After refining the biodiesels, biodiesels and diesel fuel were blended with the ratio of 20%, by volume (20% biodiesel + 80% diesel). Test fuels were named as D (diesel fuel), FB100 (false flax methyl ester), SB100 (sunflower methyl ester), CaB100 (canola methyl ester), FB20 (20% FME + 80% Diesel), SB20 (20% SME + 80% Diesel), CaB20 (20% CME + 80% Diesel). Figure 1 shows the production processes of experimental biodiesel fuels.

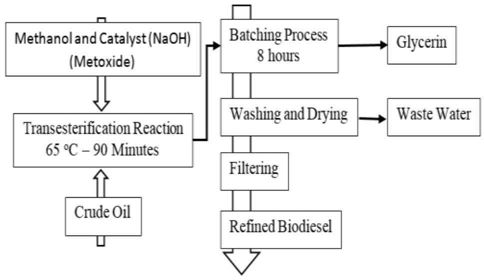

Fig. 1. Biodiesel production processes

Some critical properties of fuels were tested before the operating engine with these test fuels. Product properties were measured with; Zeltex ZX 440 NIR, Tanaka AFP-102, Tanaka AKV-202, Kyoto electronics DA-130, Tanaka APM-7, and IKA Werke C2000, for determining the cetane number, cold filter plugging point, viscosity, density, flash point and calorific value, respectively. EN 590 diesel and TS EN 14214 biodiesel standards were considered for measuring fuel properties.

2.2. Experimental Engine

Engine experimentations were practised on a single cylinder, constant speed variable compression ratio engine. The experimental engine is able to operate with both gasoline and diesel fuels. In this study, the diesel head of the engine were installed to conduct experiments. In Table 1, specifications of the engine were given. Figure 2 illustrates the test setup schematically. For testing the performance characteristics of the engine, an eddy current dynamometer was used. Specifications of the eddy current dynamometer are given in Table 2. Experiments were practiced with three different CRs (12:1, 14:1, 16:1), at 1500 rpm constant speed and under partial load of 60%. The engine was operated 15 minutes before conducting each experiment until the experimental engine reaches the stable operation conditions. Even though the experimental engine is designed to operate with higher CR (up to 18:1) than 16:1, the maximum CR was chosen as 16:1 since the increment of CR tremendously cause to increase of cylinder pressure and exhaust gas temperature and this situation deteriorate the accuracy of the experiments. Also, the experimental engine has single cylinder and works with four stroke principle which means one power stroke per four strokes. This phenomenon causes to operate of the engine vibrant, noisy and unbalanced when the cylinder pressure is very high. To be able to examine the engine experimental results accurately, the engine was operated under partial load since the forcing a single cylinder engine with full load causes to unbalanced and unstable operation.

Table 1. Test engine specifications.

Brand/Model/configuration	Kirloskar Oil Engines/240/Single Cylinder
Type	Water Cooled, Four Stroke
Displacement/Bore/Stroke/	661 cc/87.5 mm/100 mm
Maximum/Minimum Operating Speed	2000/1200 rpm
Power/Peak Pressure	3,5 Kw @ 1500 rpm/77.5 kg/cm^2
CR/IV	12:1-18:1/0-25 Deg BTDC

Table 2. Eddy current dynamometer specifications.

Model/Make	AG10/ Saj Test Plant Pvt. Ltd.
Water inlet/Load/Weight	1.6 bar/3.5 kg/130 kg
Max. Speed/Torque	10000 rpm /11.5 Nm
Continuous current amps /Hot coil voltage max.	5/60

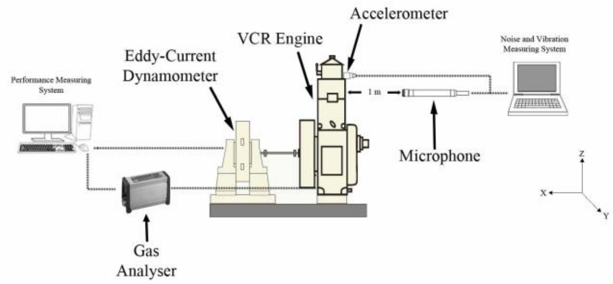

Fig 2. Schematic of experimental setup

2.3. Emission, Noise and Vibration Devices

Exhaust measurements were done with MRU Air Delta 1600 V gas analyser. Specifications of the analyser were given in Table 3.

Table 3. The exhaust analyser specifications

Specification	
CO/ CO_2/ O_2	0-10%/0-20%/0-22%
HC /NO/ NO_2/	0-20000 ppm /0-4000 ppm/0-1000 ppm
Lambda/ Ambient Temperature	0-9.99/+5º - +45 ºC
Exhaust Gas Temperature	Max 650 ºC
Accuracy	According to OIML-class 1

Vibration and acoustic data were collected via SAMURAI v2.6 software. Measurement range of the software is 2 Hz to 20 kHz.

Triaxial ICP® accelerometer was stuck on block of the engine via bonding gels to evaluate the vibration even at high frequencies. Sensitivity and measurement range of the accelerometer is 1,02 mV/(m/s²) and ± 4905 m/s², respectively. Noise level of the experimental engine was tested by free-field microphone set. Sensitivity, frequency range, and dynamic range of the microphone set is 50 mV/Pa, 3.15 Hz to 20 kHz, and 17 dB(A) to 149 dB, respectively. The microphone was positioned at 1 m away from the engine block.

Vibration measurements were gathered in longitudinal, lateral, and vertical axes. Since Root mean square (RMS) value is the most concerned indicator of vibration level (by considering the wave time history it generates an amplitude value), the experimental results were declared as RMS value as the combination of three axes

Eqs. 1 and 2 present the combination of RMS (a_{total}). In equations, a_w (m/s^2) is the weighted acceleration in an axis and T is the measurement time.

$$a_w = \sqrt{\frac{1}{T}\int_0^T a_w^2\,(t)dt} \tag{1}$$

$$a_{total} = \sqrt{a_{vertical}^2 + a_{lateral}^2 + a_{longitudinal}^2} \tag{2}$$

3. Results and Discussion

3.1. Fuel Properties

Results of the property tests of diesel fuel, sunflower methyl ester (SB100), canola methyl ester (CaB100), false flax methyl ester (FB100) and blends (B20 fuels) were given in Table 4.

Table 4. Fuel properties of test fuels.

Properties	Diesel fuel	EN590	FB20	FB100	SB20	SB100	CaB20	CaB100	ASTM D 6751	EN 14214
Density, kg/m^3	837	820−845	844	886	844	886	846	883	-	860 - 900
Cetane Number	59,47	Min 51	54,77	52	58,13	56	52,9	48	Min 47	Min 51
CFPP, °C	-11	-	-11	-10	-10	-8	-11	-12	-	Summer <4,0 Winter <-1,0
Lower heating value, MJ/kg	45,856	-	41,436	39,048	44,246	39,149	43,413	38,363	-	-
Kinematic viscosity, mm^2/s	2,76	2,0−4,5	2,97	4,38	3,1	4,5	3,2	4,7	1,9–6,0	3,5 – 5,0
Flash point °C	79,5	Min 55	91,3	>140	101,5	>140	76,7	120,5	Min 93	Min 101

The densities of biodiesels were higher compared to diesel fuel density thus B20 blends' densities were higher than diesel fuel. The calorific value of biodiesel fuels and biodiesel-diesel blend fuels were lower than calorific value of diesel fuel. Cetane number of CME was measured lower than the standards but the cetane number of its blends with diesel fuel (CaB20) were measured higher than 51 which satisfy European and American Biodiesel Standards Analysis indicated that cold filter plugging points of biodiesels and blends via diesel fuel were quite same with the diesel fuel. This is a critical property for the situations of cold working [30]. The study showed that, viscosity values of FME, SME and CME were higher than diesel fuel, however; there isn't any problem to comply with standards.

3.2. Performance Characteristics

BTHE is calculated as the ratio between engine power output and heat input provided by the fuel which is a critical performance criteria for ICEs [31]. The BTHE results of test fuels and the specific fuel consumption (SFC) results of the experiments were indicated in Figure 3 and Figure 4, respectively.

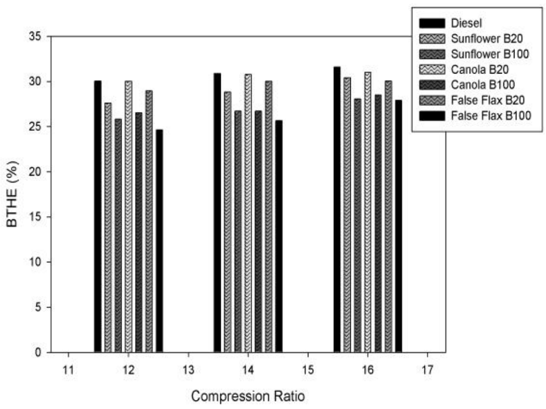

Fig. 3. BTHE results of experiments

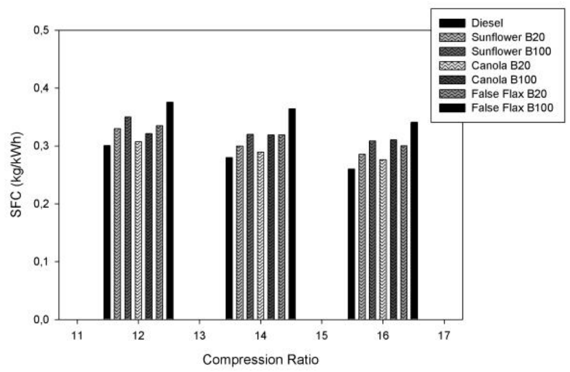

Fig. 4. SFC results of experiments

It can be seen from graphs that increasing CR improved BTHE since higher CR enhances combustion. Biodiesel usage resulted in lower BTHE since biodiesel has lower calorific value than diesel fuel. And also, lower cetane number of biodiesel and diesel-biodiesel blends caused longer ignition delay time which causes prolonged combustion duration. Increasing CR improved BTHE and SFC values for all test fuels. Increasing CR from 12:1 to 14:1 and from 12:1 to 16:1 improved BTHE 2,8% and 5,16% when engine was fuelled with diesel fuel, respectively. The maximum improvement of BTHE occurred with sunflower B20 and false flax B100 fuels and measured as 10,14% and 13,23%, respectively when the CR increased from 12:1 to 16:1. SFC values were also enhanced with CR increment. SFC values were decreased by 6,78% and 15,44% for diesel fuel when the CR increased to 14:1 and 16:1 from 12:1, respectively. The maximum improvement of SFC was with diesel and sunflower B20 fuels and measured as 13,37% and 13,45%, respectively when the CR increased from 12:1 to 16:1. The variations of experimental results when CR is increased from 12:1 to 14:1 and from 12:1 to 16:1 are given in Table 5. Theoretically, increasing CR provides better combustion and higher BTHE. The BTHE for diesel engines is shown in eq. (3).

Table 5. Variation of experimental results of test fuels with CR increment.

Fuel	**CR from 12:1 to 14:1**			**CR from 12:1 to 16:1**		
	Increment – Decrement (%)			**Increment – Decrement (%)**		
	BTHE	**SFC**	**EGT**	**BTHE**	**SFC**	**EGT**
Diesel	2,80	-6,78	12,25	5,16	-13,37	20,25
Sunflower B20	4,49	-9,09	12,18	10,14	-13,45	18,64
Sunflower B100	3,48	-8,57	11,33	8,59	-11,85	18,42
Canola B20	2,58	-5,79	8,83	3,28	-10,18	17,26
Canola B100	0,67	-0,74	9,16	7,46	-3,36	17,05
False Flax B20	3,58	-4,77	8,12	3,71	-10,41	13,01
False Flax B100	4,13	-3,00	8,60	13,23	-9,13	22,86

$$\eta_{th} = 1 - \frac{1}{r^{\gamma-1}}\left(\frac{\alpha^{\gamma}-1}{\gamma(\alpha-1)}\right) \quad (3)$$

Where;

η_{th} represents BTHE,

α represents the cut-off ratio

r represents the CR,

γ represents the ratio of specific heats (C_p/C_v).

Figure 5 shows the exhaust gas temperatures (EGT) of experiment fuels. EGT showed a linear relationship with CR increment. Biodiesel usage increased EGT for all CRs. This may be due to extra oxygen (O2) content of biodiesel and depending on this property better combustion of biodiesel [32]. The maximum EGT was measured with FB100 fuel at 16:1 CR.

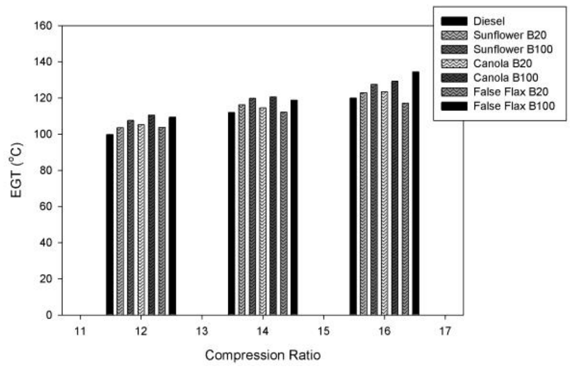

Fig. 5. EGT results of experiments

3.3. Cylinder Pressure

The combustion of diesel engine is a very complex phenomenon which depends on many parameters such as fuel, engine design, ignition timing, CR, injection profile and etc. [33]. The combustion of diesel engine is generally partially premixed and diffusive. This phenomenon depends on fuel, engine load, engine design variables, fuel injection timing, and combustion temperature [31, 34, and 35]. Figures 6-12 shows the cylinder pressure characteristics of the test fuels with CRs 12:1, 14:1, and 16:1. It can be seen from the graphs that CR increment increased peak cylinder pressure for all test fuels as it is expected. Higher CR provides the reduced ignition delay and thus the combustion occurred near the TDC (top dead center) [36]. The graphs show that the combustion of higher CR experiments occurs closer to TDC.

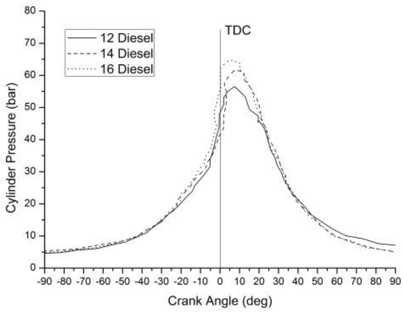

Fig. 6. Cylinder pressure graph of diesel fuel

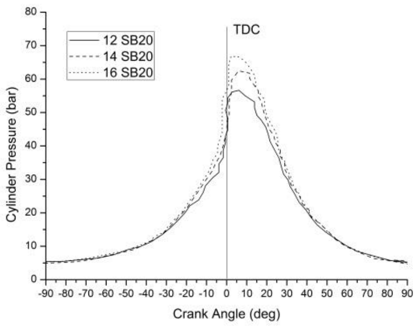

Fig. 7. Cylinder pressure graph of SB20

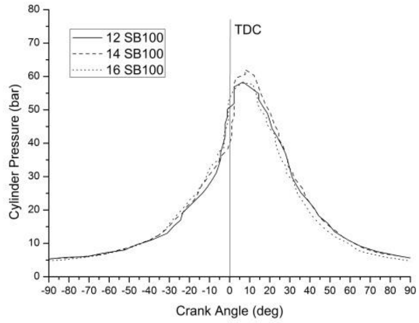

Fig. 8. Cylinder pressure graph of SB100

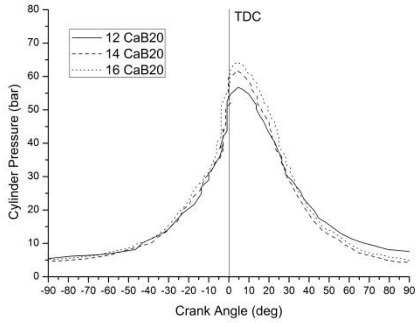

Fig. 9. Cylinder pressure graph of CaB20

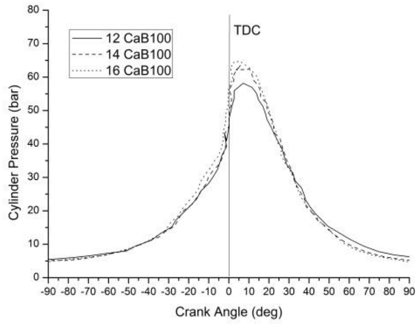

Fig. 10. Cylinder pressure graph of CaB100

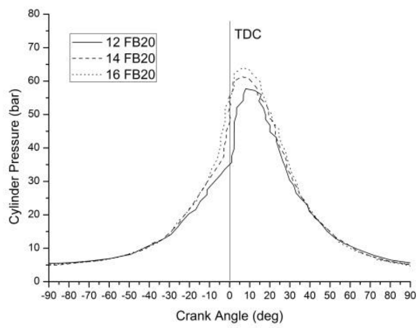

Fig. 11. Cylinder pressure graph of FB20

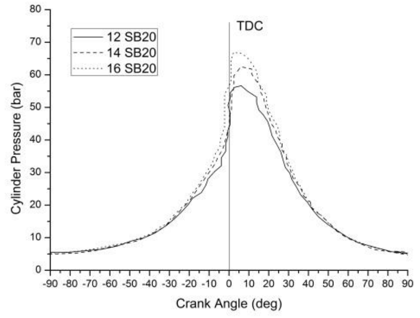

Fig. 12. Cylinder pressure graph of FB100

3.4. Emission Characteristics

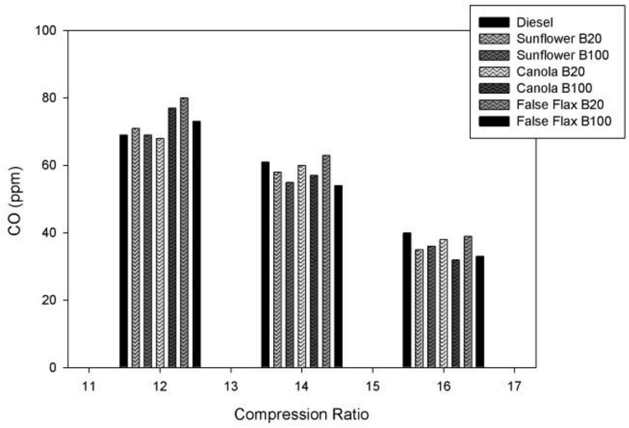

Fig. 13. CO results of all test fuels

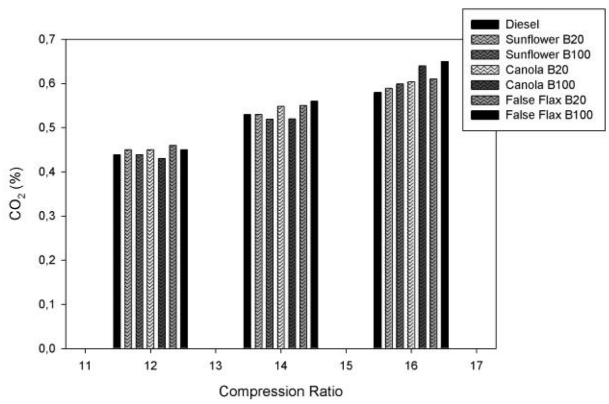

Fig. 14. CO_2 results of all test fuels

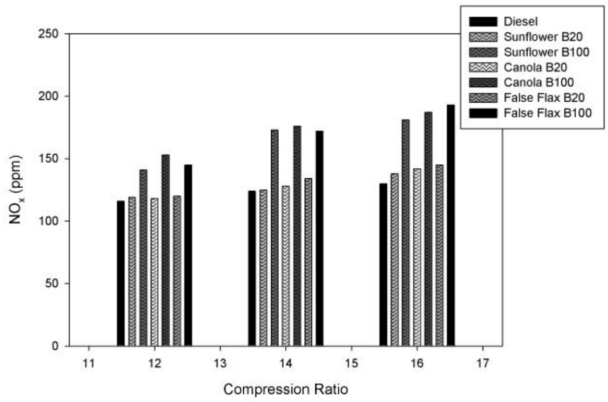

Fig. 15. NO_x results of all test fuels

3.4.1. CO Emissions

The CO emission results of the experiments were shown in Figure 13. CO formation is directly related with incomplete combustion of reactants (fuels in-cylinder) and insufficient amount of oxygen [33,34]. It is clear that higher CR provides enhanced combustion and thus lower CO emissions. Lower CO emissions was emitted by the test engine when the CR increased from 12:1 to 16:1 for all test fuels. At 12:1 CR conditions except SB100 and CaB20 fuel, diesel fuel gave better CO emission results compared to other test fuels. This may be due to lower cetane numbers of biodiesel used in experiments. With increment of CR biodiesel and biodiesel-diesel blends resulted with lower CO emissions. Biodiesel fuels contain extra O_2 content in their chemical composition. So, biodiesel usage enhances the combustion and CO emissions are converted to CO_2 emissions. Increasing CR from 12:1 to 14:1 and 16:1 improved CO emission 11,59% and 42,02%, respectively for diesel fuel. The maximum improvement was occurred with CaB100 fuel in terms of CO emissions.

CO_2 Emissions

Variation of CO_2 emissions are illustrated in Figure 14. It can be seen from the graphs higher CR experiments resulted with higher CO_2 emissions since as CR is increased the combustion is improved and thus CO compositions are converted to CO_2 emissions. Also usage of biodiesel caused to increasing of CO_2 emissions at high CRs. This is an expected phenomenon because carbon molecules are mostly converted to CO or CO_2. As the oxidation gets better carbon molecules are converted to CO_2 substantially. CO_2 emissions were higher 20,78% and 32,15% at CR 14:1 and 16:1, respectively, compared to CR 12:1 for diesel fuel.

3.4.2. NO_x Emissions

NO_x results of the fuels are illustrated in Figure 15. Higher CR means higher cylinder pressure and higher cylinder temperature. Increased cylinder temperatures are the main cause of more formation of NO_x emissions. NO_x formation is mainly dependent on end-combustion temperature and flame velocity [35-39]. Also biodiesel usage increased NO_x emissions caused by higher combustion temperature of biodiesels. Experiments revealed that higher CR experiments resulted with higher NO_x emissions. Increasing CR from 12:1 to 14:1 and 16:1 increased NO_x emissions, 6,89% and 12,06% for diesel fuel, 5,04% and 15,96% for SB20, 7,45% and 12,42% for SB100, 10,18 and 31,48% for CaB20, 11,66%, 1,73% and 8,09% for CaB100, and 20,83% for FB20 and also 4,24% and 16,96% for FB100, respectively.

3.5. Noise and Vibration

Operation of internal combustion engine is the main source of vibration and noise in a vehicle. Therefore, throughout the experiments, noise and vibration characteristics of the test engine were also measured. As it can be seen in Fig. 16, the results showed that usage of biodiesel decreased the vibration of engine block compared to conventional diesel fuel since biodiesel contain extra oxygen thus combustion of biodiesel has greater rate than diesel fuel [40]. This is the primary reason of NO_x emissions increments as well. Increment of CR caused to decrement of engine vibration with all test fuels. Gas-flow, mechanical processes and combustion are the primary sources of noise generation in a diesel engine [41]. In this study, since A-weighted sound pressure level (SPL) is resemble to human ear sensation, it is used to processing of SPL results. Biodiesel fuels are also caused the decrement of SPL compared to conventional diesel fuel and also, maximum SPL of the test engine was occurred with 12:1 CR, and the least value was measured at 16:1 CR (Fig. 17) since biodiesel addition and higher CR caused to lower vibration acceleration of engine body [42].

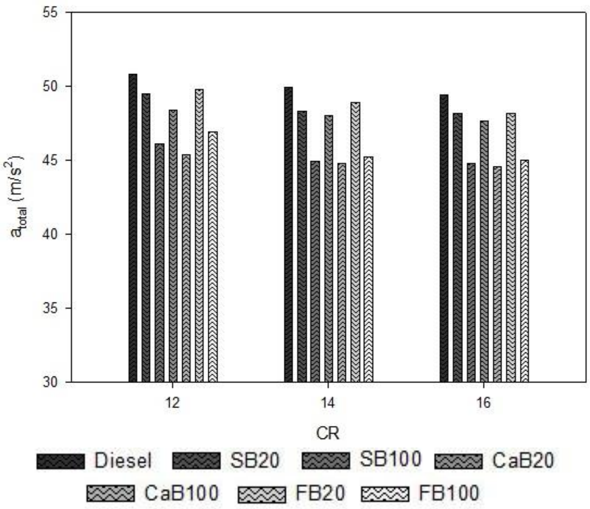

Fig. 16. a_{total} results of VCR engine

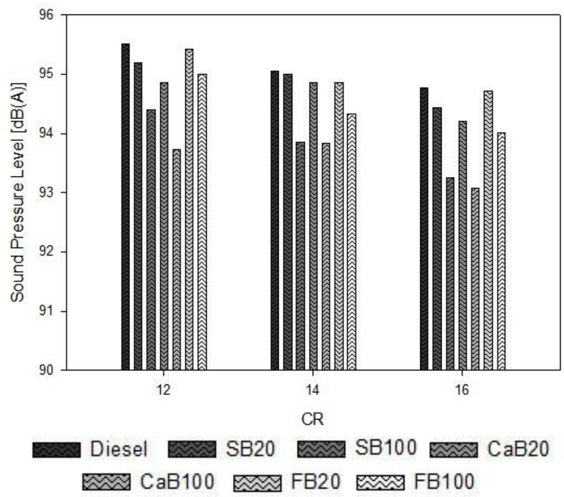

Fig. 17. SPL of VCR engine

4. Conclusion

This experimental study was practised to observe the performance, combustion, emission, noise and vibration characteristics of a diesel engine at various CR fuelled with diesel and B20 fuels. In the experiments CR of the test engine was set as 12:1, 14:1, and 16:1.
According to results, the followings can be concluded;

- Maximum of mean BTHE (31,6%) was observed at 16:1 CR when engine was operated with conventional diesel. Biodiesel blend (B20) usage caused decrement of BTHE values compared to diesel fuel.
- Increasing CR improved SFC due to better BTHE for all test fuels. Compared to diesel fuel diesel-biodiesel blends and biodiesel fuels increased SFC slightly.
- EGT was increased with higher CR and biodiesel usage.
- Engine vibration decreased with biodiesel usage. Increment of CR caused the decrement of vibration further.
- Maximum SPL was observed with 12:1 CR, and the least value was occurred at 16:1 CR. Usage of biodiesel fuel when compared with diesel fuel also decreased SPL of the engine.

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