Effect of Piston Geometry on Performance Characteristics of VCR Engine with and without EGR when Fueled with Blends of Methyl Ester

Shrikant V. Baste[*], *Sudhakar S. Umale*
Sardar Patel College of Engineering Mumbai 58 Maharashtra, INDIA
[*]*shrikantv24bsv@gmail.com*

ABSTRACT

The growing population and exhaustion of fossil fuels necessitate our search for new sources of energy. The study for this research encompasses an amalgamation of interest in alternative fuels, advanced engine technology such as variable compression ratio VCR, engine component modification, and a methodical approach to testing for assessing the effects on key performance of the engine. A 3.5 kW compression ignition (CI) engine was fueled with blends of behada, chicken fat, and turmeric oil methyl ester. Engine operating parameters, such as the compression ratio (CR), rate of exhaust gas recirculation (EGR), and piston top geometry, are optimized to maximize engine performance. CI engine was modified by changing the piston head (square and tangential groove top) for methyl ester diesel blend operations. In the study, diesel fuel is designated as B00 and methyl ester as B20. The influence of compression ratio (CR16 and CR18) with exhaust gas re-circulation (EGR 0% and EGR 10%) was evaluated. The key performance indicators: brake thermal efficiency (BTE), brake-specific energy consumption (BSEC), brake-specific fuel consumption (BSFC), air-to-fuel ratio (AFR), and exhaust gas temperature (EGT) are investigated. Results indicate that an increase in BTE accompanies an increase in load, suggesting enhanced thermal efficiency with increased power output. The consequence of VCR is also investigated, and it is determined that a higher CR results in a higher BTE due to an increase in compression pressure and temperature, thereby enhancing combustion. Due to the re-combustion of unburned hydrocarbons with the addition of EGR at a 10% rate, BTE increases further. Utilizing a piston geometry with tangential grooves and methyl ester blends also contributes to increased BTE. BSEC increases with increasing load, with an important rise observed when operating at maximum capacity. However,

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at CR 18, BSEC decreases as a result of enhanced combustion efficiency. EGR has different effects on BSEC depending on the geometry of the piston and the kind of fuel used. Enhanced air-fuel blending and re-combustion of unburned hydrocarbons reduce the BSEC of the engine. The tangential groove top piston operates with 10% EGR. Similar to BSEC, BSFC decreases with increasing CR and improves with the use of a piston with a tangential groove and 10% EGR operation. AFR decreases as the consumption of fuel increases to meet the power demand, and higher CR values result in a lower AFR. EGT rises with load, and CR18 has a lower EGT than CR16 as a result of a higher compressing temperature and pressure. 10% EGR operation reduces EGT by decreasing the concentration of oxygen in the combustible area.

Keywords- *CI Engine; Methyl Ester Blends; Variable Compression Ratio; Exhaust Gas Recirculation; Piston Geometry; Performance*

Introduction

Diesel engines are renowned for their superior power and efficiency. Diesel fuel plays a crucial part in worldwide energy consumption, providing power to numerous industries including transportation, industry, agriculture, and power generation. Furthermore, the depletion of fossil fuels, the increase in fuel prices due to inflation, and the strict emissions regulations pose significant obstacles to the utilization of diesel engines, as previously stated. To tackle these issues, researchers must employ creative methods to advance biodiesel feedstock and blend mixing, enhance current combustion processes, and build a reliable utilization of biodiesel as a feasible substitute for conventional fossil fuels.

The constant evolution of internal combustion (IC) engines has been driven by the need for increased fuel efficiency, decreased emissions, and increased output power. To enhance the performance of IC engines, researchers and engineers have studied a number of strategies. One area of research involves the use of different fuels in the manner of methyl ester mixtures within CI engines [1]. Methyl ester compounds, additionally referred to as biodiesel, have been sustainable and possess favorable combustion characteristics. The present research aims to determine the efficacy of CI engines using diesel methyl ester mixtures, as well as the effects of modifying engine settings like CR, and EGR rate, along with piston configuration. Biodiesel usage has garnered substantial interest due to the prospect of reducing the release of greenhouse gases and dependency on fossil fuels [2].

Vegetable oils or animal lipids have garnered considerable attention in the sector of renewable energy. Biodiesel, referred to just like methyl ester compounds, possesses numerous beneficial characteristics which include high cetane number, increased lubricity, along reduced sulfur content levels [3].

Those features render methyl ester an attractive alternative propellant in CI engines. Biodiesel has been shown to emit fewer pollutants such as carbon monoxide (CO), hydrocarbon (HC), along particulate matter (PM) compared with traditional diesel fuel. Additionally, biodiesel combustion produces reduced sulfur oxides (SOx) and volatile HC, which contribute to air contamination and pose health risks. Therefore, biodiesel can reduce the environmental impact by improving combustion. CI engines efficacy and efficiency are dependent on the CR [4]. The change in CR value improves control over the combustion operation and optimizes engine performance for different operating conditions. The outside air temperature along with the quantity of the air-fuel blend can be tailored for combustion that was effective through modulating the reduction rate. This investigation would examine the influence of changing CR parameters of a CI engine powered with methyl esters combinations. By varying the compression ratio, it would be easy to identify the optimal ratio that maximizes thermal efficiency and minimizes emissions. This strategy can enhance CI engines' efficiency on the road and reduce their environmental impact [5].

EGR has become a renowned technique to decrease nitrogen oxide (NOx) that escapes after combustion. By recycling certain amounts of this exhaust gas via the inlet manifold, the level of oxygen within the combustion chamber was reduced, resulting in lower peaking burning temperatures along with a corresponding reduction in NOx formation [6]. The methyl esters compounds are utilized within a CI engine, and the impact of a constant, reduced EGR rate upon combustion properties along with pollutants can be examined. The evaporation from the returned exhaust gases helps towards an additional decrease of the maximum temperatures, thereby reducing the amount of NOx released [7]. The intention of this investigation was to determine an appropriate EGR assessment that creates an equilibrium between lowering emissions along engine performance. The structure of the injector has a substantial effect on its efficiency and pollutants. The combustion process, the conveyance of heat, and airflow within an engine are affected by the piston's shape. In CI engines, optimizing the piston geometry can increase efficiency and decrease emissions [7].

Vedagiri et al. [8] examined the effects of various piston geometries on the efficacy of a CI engine powered by methyl ester mixtures. The variations would be kept to vessel shape, piston crown design, and hydraulic bowl depth to determine their effect on combustion characteristics, fuel economy, and emissions. By optimizing the geometry of the piston, there was an increase in engine efficacy and a decrease in its environmental impact. The study investigated the connection between a compression ratio, a constant rate of chilled EGR, and the geometry of the piston [9]. These parameters can be optimized synergistically to obtain the optimal performance as well as emissions characteristics for a CI engine operating on methyl ester mixtures. On a test apparatus outfitted with a CI engine, experimental examinations were conducted. Simulating actual operating conditions, the engine was operated under a variety of load conditions. To assess their impact on combustion, emissions, and performance parameters, methyl ester mixtures would be incorporated with conventional diesel fuel in varying proportions. In order to evaluate the combustion feature of the CI engine, additional emission parameters like peak pressure, heat rejection rate, ignition time, and combustion were measured [10].

Methyl ester, a fuel used in compression ignition engines, is being explored as an alternative fuel for engine performance. The use of methyl ester in engine design suggests a shift towards sustainable alternatives. The study explores the use of variable compression ratio technology and the diverse blend sources of methyl ester, such as behada, chicken fat, and turmeric oil. The piston head design changes for methyl ester blends suggest engine components can be tailored to improve the performance characteristics of the engine. The study also explores the relationship between compression ratio and engine performance. The goal is to reduce reliance on traditional fossil fuels and mitigate environmental impacts caused by varying emissions from compression ignition (CI) engines.

Significance of the study

The importance of this investigation stems from the experimentation of the efficiency variables of CI engines with methyl ester combinations, in addition to the precise adjusting of engine parameters which includes CR, EGR rate, along pistons geometries. As a consequence of enhanced combustion and performance characteristics, the investigation indicates the rate of EGR at various compression ratios improves BTE by re-combusting unburned hydrocarbons. Overall, the results provide useful information for refining engine performance and fuel economy with methyl ester blends.

Experimental Set-Up and Methodology

Figure 1 depicts the study's experimental arrangement of a VCR engine. The different geometries of the piston top are one of the effective methods for enhancing the performance of CI engines [11]-[14]. In this experiment, the standard piston of the CI engine was replaced by a piston with a square groove top piston (Figure 2(a)) and a piston with a tangential groove top (Figure 2(b)). This is similar to the work carried out by Stephan et al. [11]. Assuring that all electrical connections, including those to the sensor, battery, and power supply, are severed. The flat piston of the standard diesel engine is manually removed using a 9/16-inch spanner, and the square and tangential groove top piston is installed using push rods. Reconnect the engine exhaust and water outlet connections to the engine block. During piston head replacement, the compression ratio of the engine has been altered and observed to be between

16 and 18. The reduction or improvement in CR values can be attributed to the advancement of novel diesel engines that are very efficient and have low emissions. Enhancing the performance and evaluating the combustion of the CR effect holds significant value [4], [7], [15]-[17]. The pressure needed for injection was maintained at 600 bar [20]. The engine operating parameters have been laid out in Table 1.

The experimental combination consists of B00 and B20. B00 denotes diesel fuel in its purest form, while B20 signifies diesel fuel blended with 20% methyl ester. The researchers have also proposed that blending 20% of biofuel by volume with diesel fuel yields notable advantages in comparison to the use of pure diesel fuel [14], [20]-[21], [27]. The EGR technology was utilized between 0% and 10% [20].

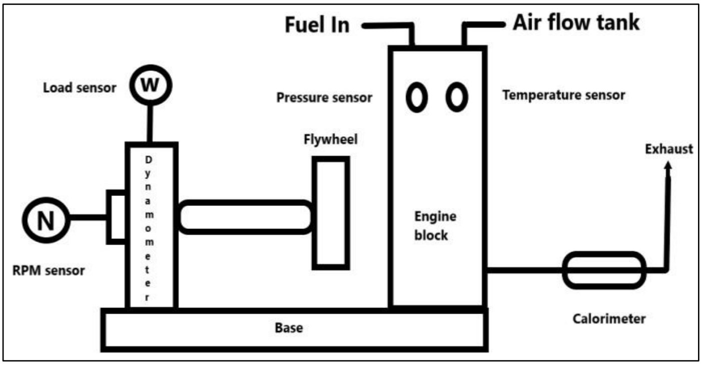
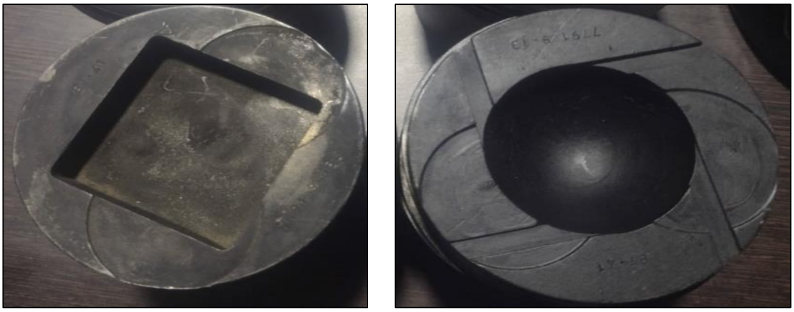


Figure 1: Experimental research engine



(a) (b)

Figure 2: (a) Square, and (b) tangential groove top piston

Table 2 provides the detailed specifications for the engine used for the experimentation. An eddy current dynamometer controlled by a computer was attached to the engine. The piezoelectric pressure transducer and crank angular sensor have been mounted on the engine in order to track the cylinder's pressure. Each pressure monitor or encoding signal was connected to an amplifier to generate a signal for the combustion analyzer to evaluate. The engine combustion analyzer was used to evaluate and determine cylinder combustion variables such as ignition delay, start of combustion, and end of combustion [20].

Table 1: Engine operating parameters

Run	Compression ratio (CR)	Injection of pressure (IOP), bar	Injection time (IT), in degrees	EGR
1	16	600	23	0%
2	16	600	23	10%
3	18	600	23	0%
4	18	600	23	10%

Table 2: Diesel engine parameters

Parameter	Description
Engine makes	Kirloskar Tv1 VCR Engine 3.5 kW at 1500 RPM
Number of cylinders	1
Cycles	4 Stroke
Engine timing	23^{o} bTDC
Compression ratio	12 to 18

The properties of methyl ester are given in Table 3 according to the American Society for Testing and Materials (ASTM) 6751 standard.

Table 3: Properties of methyl ester

Description	Reference standard ASTM6751	Reference unit	Blend ID	
			B00	B20
Density	D 1448	gm/cc	0.830	0.833
Calorific value	D 6751	MJ/Kg	43.50	42.89
Cetane number	D 613	--	49	49.52
Viscosity	D 445	mm^2/sec	2.70	2.84

Results and Discussion

Brake Thermal Efficiency (BTE)

Figure 3 shows BTE increases with the increase in load from 0 kg to 15 kg, as load increases fuel injection increases to get more power due to which thermal efficiency increases [20]-[22]. The CR16 shows 23.4% BTE while CR18 shows 26.9% BTE at 15 kg load operation. This 14.9% higher BTE for CR18 than CR16. This increase in BTE was observed due to a higher compression ratio that shows more initial and final in-cylinder compression pressure and temperature.

The higher compression pressure and temperature improve more air-fuel mixing and hence more rapid and complete combustion, resulting in more BTE [22]-[23], [27]. Figure 1 shows a significant improvement in BTE of 22.8% more with CR18 than CR16 [22]. This would be with the aid of tangential groove top piston groove and higher compression ratio improvement in air swirl, air-fuel mixing and thus more rapid and complete combustion even with methyl ester blend [21].

Compression ratio is a critical factor for achieving efficient combustion [23]. The higher CR helps to raise the pressure and temperature which would help to achieve efficient combustion [23]. Further, the high compression ratio is essential for achieving combustion, but it can lead to knocking or pre-ignition at high loads [18]-[22]. Besides, low CR leads to incomplete combustion or white smoke with an increase in emission and reduced fuel efficiency [23].

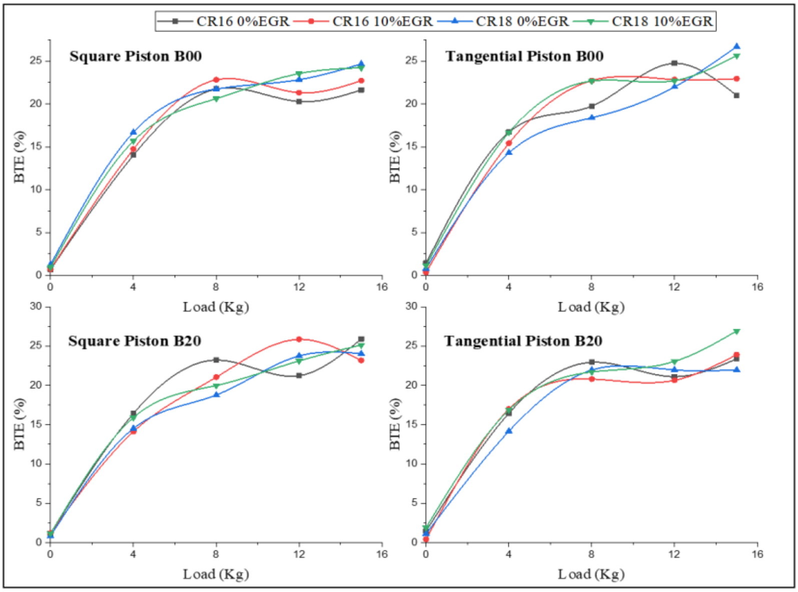


Figure 3: Variation in BTE with load

The 10% EGR with CR16 shows more BTE than without EGR at CR16 due to the re-burning of un-burnt hydrocarbons. Hence, CR16 with 10% EGR operation was recommended. Similar noting of tangential groove top piston with B20 fuel have been mentioned. Similarly, the tangential groove top piston with B20 fuel and 10% EGR showed BTE 23.0% and 26.93% at 12 kg and 15 kg load, respectively, then 21.98% and 21.97% at the same operation without EGR. This relative improvement in 5% to 10% BTE with 10% EGR was achieved as a combined effect of EGR, VCR, blend, and piston geometry [14], [20].

The fuel blend and piston geometry have a positive effect on BTE. Fuel blends with B20 and square groove top pistons have shown higher BTE i.e., 23.75% and 24.0% at 12 and 15 kg loads, respectively [14]. Followed by the square groove top piston with B00 and tangential groove top piston with B20 fuel showed about 21.9% BTE at full load. Tangential groove top pistons with a full load and B00 fuel showed a significant BTE of 26.6% and higher among all [14]. Formula to calculate BTE;

$$\text{BTE} = \frac{Brake\ power}{Heat\ Energy\ supplied} \tag{1}$$

where brake power is $2\pi NT/60$ and heat energy supplied is $m_f \times C_v$.

Brake Specific Energy Consumption (BSEC)

Brake specific energy consumption is the amount of energy required to produce specific or equivalent power per unit of time [14], [21]. VCR technology has an impact on BSEC by allowing for the optimization of the combustion process based on different operating conditions.

Figure 4 shows low load and CR 16 has shown less BSEC of 19.5 MJ/kWh at least at all loads and EGR operation. B20 fuel at 12 kg load shows lower BSEC 53 MJ/kWh at higher load and higher CR with 0% EGR and tangential groove top piston geometry. Hence, low loads and a lower compression ratio can be used to reduce BSEC by improving combustion efficiency and reducing energy losses due to pumping. At high loads, a higher compression ratio can be used to increase power output while maintaining fuel efficiency, leading to lower BSEC [23].

BSEC increases with an increase in load as shown in Figure 4. At part load, BSEC was 20-30 MJ/kWh while at full load 60 MJ/kWh to 70 MJ/kWh. It can be seen that the increase in BSEC is 33% to 42% from part load to full load operation was due to an increase in fuel consumption in order to meet power requirements [23]. In all operations, about 15% less BSEC has been reported by CR18 compared to CR16. The higher compression leads to improved combustion efficiency and less fuel and energy consumption for the same power [20].

As EGR increases for CR16 and square groove top piston with B00 fuel have shown an increase in BSEC [20] because in a square chamber, less burning of fuel causes increases in fuel and energy consumption. As EGR increases further drop in oxygen and air fuel mixing causes less combustion and rise in BSEC about 5% for load operation at CR16 and 10% EGR for square groove top piston with B00 as fuel. However, the tangential groove top piston has shown opposite behavior, for B00 and B20, for CR16 and CR18, as EGR increases from 0% to 10%, about an 8% decrease in BSEC has been reported [14], this may be due to hemispherical bowl at center and tangential groove at periphery causes more swirl and air fuel mixing. With 10% EGR re-burning of unburnt hydrocarbon happens hence relatively less fuel and BSEC was required. At 10% EGR, BSEC reported 66.9 MJ/kWh, 64.3 MJ/kWh, and 57.9 MJ/kWh compared to 73.2 MJ/kWh, 66.4 MJ/kWh, and 70.7 MJ/kWh [20].

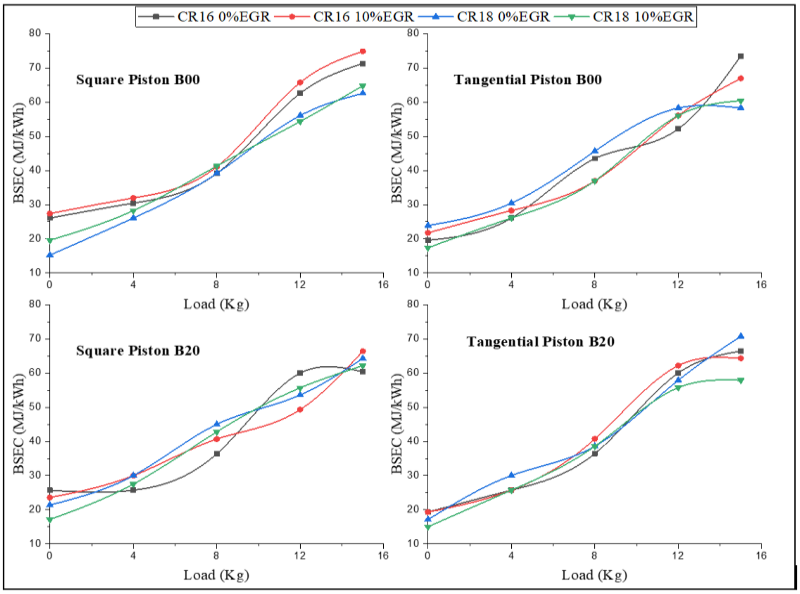


Figure 4: Variation in BSEC with load

Piston bowls can affect the air-fuel mixture formation, which can affect the combustion efficiency and BSEC [11], [14]. A well-designed piston bowl can promote more efficient combustion [11], [14], leading to lower BSEC. A higher compression ratio results in a greater degree of compression of the air within the cylinder can lead to more efficient combustion [14] and lower BSEC, while a lower compression ratio can lead to higher BSEC. Formula to calculate BSEC;

$$\text{BSEC}=\frac{r}{P} \tag{2}$$

where r is standard fuel consumption in grams per second and P is power output in watts.

Brake Specific Fuel Consumption (BSFC)

Brake specific fuel consumption (BSFC) is a measure of an engine's fuel efficiency, defined as the amount of fuel consumed per unit of power output [27]. Piston geometry, VCR, EGR, and blends have an impact on brake specific fuel consumption (BSFC) of diesel engines shown in Figure 5.

The load increases fuel consumption increase contradictory [27], brake specific fuel consumption decreases. BSFC from no load or part load to full load decreases from 0.6 kg/kWh to 0.31 kg/kWh. This almost 50% decrease in BSFC with an increase in load was due to a specific power output of the engine increases with an increase in load [24], [27]. Also, at full load, power as well as heat produced was utilized more efficiently hence brake thermal efficiency is reported more at full load. Further effective utilization of fuel and power happens at full load. Brake specific fuel consumption shows similar trends like compiling to BSEC. Besides, as the load increases BSFC decreases due to an increase in output power with an increase in load and torque [27]. The amount of heat produced in the above BSEC with an increase in load is utilized for the use of full power output.

From Figure 5 it can be noted as CR increases from CR16 to CR18 BSFC decreases by 11% from 0.38 kg/kWh to 0.34 kg/kWh for B00 fuel and without EGR operation illustrated in Figure 5. About 11% higher BSFC [14], [24] was reported by CR16 compared to CR18 at full load with, without EGR and both piston geometry operations. This indicates that at full load operation, CR18 produces more combustion efficiency and less fuel consumption for equivalent power [20]. Also, CR18 attracts better air fuel mixing, higher temperature pressure, and shorter combustion duration. All together CR18 gains less BSFC compared to CR16.

Further, with an increase in EGR by 10%, B20 fuel with tangential groove top piston geometry for both CR showed a decrease in BSFC as a result of proper and homogeneous combustion and re-burning of UHC with B20, tangential groove top piston. For tangential groove and EGR 10% for both fuel B20 and B00, compared to the same operation at square groove top piston showed 3% - 6% less BSEC [14]. This may be due to the tangential groove top piston with groove and EGR improves less ignition delay, high flame propagation, more rapid combustion, or shorter combustion duration resulting in less BSFC. At tangential groove top piston with 10% EGR, B20, B00 operation BSFC was 0.31 Kg/kWh, 0.35 Kg/kWh, 0.32 Kg/kWh, and 0.36 Kg/kWh are less compared to square groove piston, 0% EGR, B20 and B00 fuel. Formula to calculate BSFC:

$$\text{BSFC}=\frac{r}{P} \tag{3}$$

where r is standard fuel consumption in grams per second and P is power output in watts.

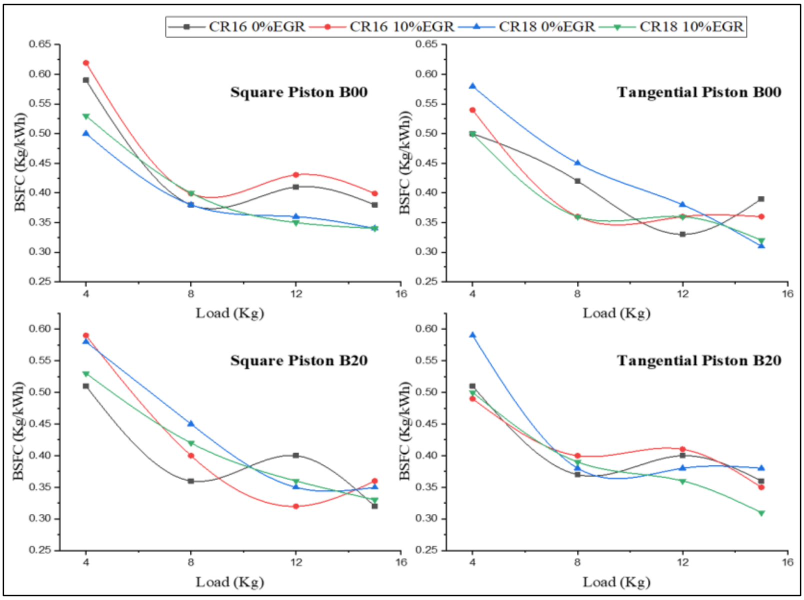


Figure 5: Variation in BSFC with load

Air Fuel Ratio (AFR)

Air fuel ratio is the mass of air (kg/h) induced in suction to the mass of fuel (kg/h) injected in combustion. In diesel engines the amount of air alone is either naturally or turbocharged induced into suction [25]-[26]. Fuel is directly injected into the compression stroke. Hence, air-fuel ratio is a unitless parameter that defines how reach or how lean is combustion mixture. Diesel engines have an amount of air fixed only the amount of fuel can be controlled. Hence, diesel engines typically operate at a lean mixture of 16-25 air-fuel ratio.

The engine runs at a constant speed, hence the amount of air breath is almost constant in a naturally aspirated engine [26]. Also, CI engines are well-known as quality-governed engines. The air flow rate was 26 kg/h - 27 kg/h at 1500 rpm. Now, the amount of fuel injected in direct injection is controlled by a pump assisted by a mechanical governor. As seen from Figure 6 shows a decreasing nature with an increase in load for all operations [27]. The air fuel ratio for no load or part load was 50-70 and decreased to 20 at full load [26]-[27] as shown in Figure 6. This shows as the load increases the amount of fuel required increases to meet required power [26]-[27]. Hence, as fuel alone increases air fuel ratio decreases. CR18 shows a higher air fuel ratio than CR16 in square groove top piston operation. Conversely, CR16 and CR18 with tangential groove top piston groove show closer air fuel ratio at respective operation. Because of the tangential groove it overcomes VCR and EGR effects and produces a similar swirl and tumble ratio [14]. Hence similar air fuel mixing as modification of tangential groove over different VCR and EGR.

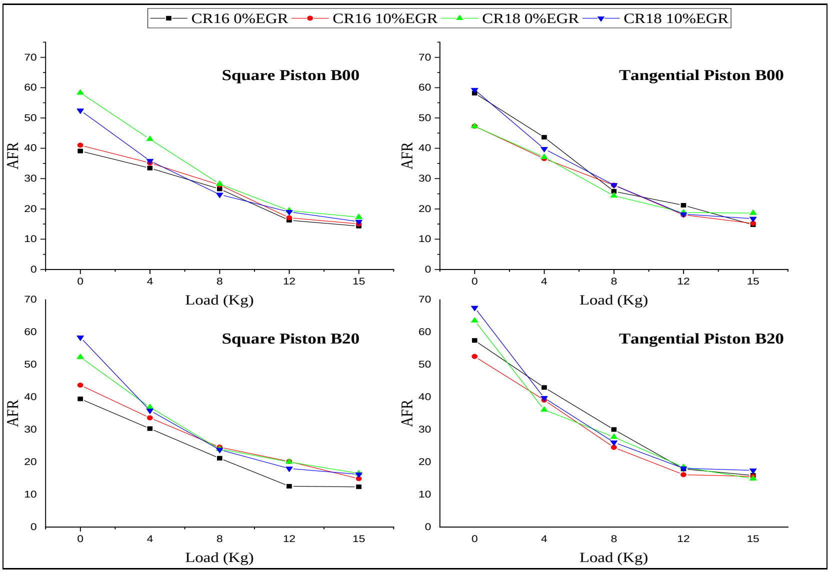


Figure 6: Variation in AFR with load

Further, the square groove top piston bowl has shown a higher air-fuel ratio for B00 fuel at low load and high load fuel However, for B20 fuel tangential groove top piston has shown high AFR at low load and square groove top piston with B20 fuel has shown high AFR at high load. AFR ratio observed, with and without EGR than all respective operations with tangential groove top piston geometry.

Exhaust Gas Temperature (EGT)

Exhaust gas temperature is the temperature of exhaust gas emitted from the engine after combustion stroke [21]. According to literature studies, exhaust gas temperature is a critical parameter in the operation of internal combustion engines, particularly in diesel engines [22]. It is used to optimize engine performance, protect the engine from damage, reduce emissions, and ensure safety. EGT is also closely linked to emissions. High EGT can increase emissions of harmful pollutants such as NOx and PM [22]. Monitoring EGT can help optimize engine operation to reduce emissions and comply with environmental regulations.

Exhaust gas temperature increases from 150 ℃ to 450 ℃ with an increase in load from 0 kg to 15 kg shown in Figure 7. As load increases fuel consumed increases hence combustion and EGT increases [21], [26]-[27].

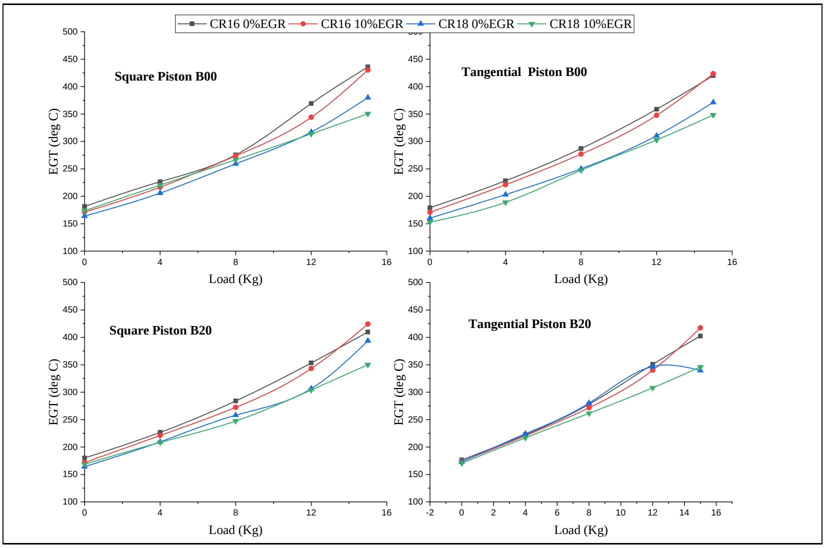


Figure 7: Variation in EGT with load

Further, EGT reported by CR16 was more than CR18 for both fuels, EGR and piston geometry. EGT noted by square groove top piston B00, tangential groove top piston B00, square groove top piston B20, tangential groove top piston B20 at CR 16 and CR18 with 0% EGR are 435 ºC, 420 ºC, 409 ºC, 402 ºC and 379 ºC, 371 ºC, 393 ºC, and 339 ºC, respectively shown in Figure 7. By adjusting the compression ratio, VCR technology can improve combustion efficiency and minimize energy losses, leading to lower exhaust gas temperature and improved engine efficiency by better atomization and vaporization [20], [22].

EGT reported more in VCR16 than CR18 may be due to less compression temperature and pressure of low CR increasing ignition delay period and hence more combustion duration, resulting in more afterburning and exhaust gas temperature in low CR [7], [22]. Further, EGT reported 10% EGR in all operations was low compared to EGR or without EGR operation. This may be due to 10% EGR introducing a good amount of fresh air in combustion which reduces oxygen and with this in cylinder and exhaust gas temperature was reduced. This helps to reduce NOx emission [7], [20].

Conclusion

The geometry of the piston has an important impact on the engine's heat release rate, cylinder pressure, and temperature. The combustion and performance of the piston with a square groove top and tangential groove top were superior.

- The square groove top piston B00 and tangential groove top piston B00 show an increase in BTE as the load increases, indicating a positive correlation between power output and thermal efficacy.
- The improvement ranges from 0% to 15%. Comparing the square groove top piston B20 and tangential groove top piston B20, the BTE values are higher with an improvement of approximately 22.8%. This demonstrates that the use of methyl ester molecules as a fuel enhances thermal efficiency.
- Examining the effect of VCR, it is determined that the BTE for CR18 is 14.9% higher than that of CR16, suggesting an important rise in thermal performance.
- BSEC showed an increase of 33% - 42% compared to 20 MJ/kWh - 30 MJ/kWh at partial load towards 60 MJ/kWh - 70 MJ/kWh at maximum load.
- Comparing the BSEC for an engine with CR18 and CR16, the engine with CR18 shows a 15% less BSEC under all conditions of use. This decrease in BSEC was attributed to the higher compression ratio of CR18, which improves combustion efficiency.
- The use of methyl ester blends as fuel in CI engines positively affects BTE by increasing thermal efficacy and improving combustion efficiency.
- VCR has a significant impact on BTE, with higher compression ratios resulting in higher thermal efficiency.
- Brake Specific Energy Consumption (BSEC) increases with load, but engines with higher compression ratios have lower BSEC due to improved combustion efficiency.
- The presence of EGR reduces BSEC by promoting the re-combustion of unburned hydrocarbons and enhancing combustion.
- Tangential groove top pistons improve BSEC by increasing air turbulence and air-fuel blending.
- BSFC decreases with increased engine load and higher compression ratios, indicating improved engine efficiency and reduced fuel consumption. EGR and piston geometry with tangential grooves contribute to reduced BSFC by enhancing combustion efficiency.
- Optimal performance was achieved with tangential grooves, EGR at 10%, and B20 fuel, resulting in lower BSFC.

- Air Fuel Ratio (AFR) decreases as fuel injection increases, but at higher compression ratios and EGR increase AFR, optimizing combustion performance.
- Engine parameters such as VCR, EGR, piston geometry, and fuel mixtures significantly affect AFR, which should be carefully calibrated for enhanced performance and pollution control.
- Exhaust Gas Temperature (EGT) increases with engine load, but higher compression ratios and piston geometries can lower EGT due to improved combustion efficiency.
- EGR reduces EGT by limiting oxygen availability and lowering combustion temperature, resulting in reduced NOx emissions.
- Engine load, compression ratio, piston geometry, and EGR rate are important factors influencing EGT in CI engines, with implications for fuel consumption and emissions.

Contributions of Authors

The authors confirm the equal contribution in each part of this work. All authors reviewed and approved the final version of this work.

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Conflict of Interests

All authors declare that they have no conflicts of interest.

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