The effects of compression ratio and combustion initiation location on knock emergence by using multiple pressure sensing devices

Kalim Uddeen, Hao Shi, Qinglong Tang, Gaetano Magnotti, James Turner

Clean Combustion Research Center, King Abdullah University of Science and Technology, Thuwal 23955-6900, Saudi Arabia

Tel: +966545395987; email: hao.shi@kaust.edu.sa

Abstract

Knock research is an essential study because knock limits spark-ignition (SI) engine power output, durability, noise, fuel consumption, and emission performance. The thermal efficiency of an engine can be improved by increasing the compression ratio, but at the same time it leads to the possibility of end gas autoignition inside the chamber. The objective of this work was to show the effect of three different compression ratios (CRs) 8.5, 9.5 and 10.5 on the mechanism of knock. In order to achieve this four equispaced spark plugs were fitted around the circumference of a special metal liner to initiate flame fronts from those plugs by firing with different spark approaches (e.g., spark timing, number, and location). In addition, six pressure sensors were installed at various locations to precisely record the autoignition event by monitoring pressure oscillations, combustion characteristics, and knock intensity. In-cylinder pressure and heat release rate (HRR) analyses were applied to distinguish the knocking combustion for the three different CRs. The results showed that a greater number of spark plugs produced more stable combustion even for a delayed spark timing (ST) than a single spark plug, but also increased pressure oscillations, HRR and knock propensity with higher CRs due to an increase in pressure and temperature inside the cylinder. The maximum amplitude of pressure oscillation (MAPO) method was used to determine the knock intensity, and it was observed that at the lowest CR of 8.5 three spark plugs gave higher MAPO values compared to four spark plugs for the same operating conditions. However, four spark plugs instigated higher MAPO values than three spark plugs for the higher CRs of 9.5 and 10.5 because, with the increase of CR

and spark plug numbers, the pressure and temperature were increased during the combustion event, which was coupled with the compression effect on the unburned end gas mixture. Additionally, Fast Fourier transform (FFT) and wavelet methods were implemented to observe the frequencies induced during knock. It was found that sparking four plugs provoked various vibration modes in different amplitude ranges with the different CRs.

Keyword

Knock mechanism; Spark-ignition (SI) engine; Compression ratio; Fast Fourier transform; Wavelet

1. Introduction

In recent years, the emissions from internal combustion (IC) engines have become a serious concern worldwide. Such engines convert chemically bound energy in the fuel to generate useful mechanical work. They mostly utilize hydrocarbon fuel and so produce many harmful species such as CO₂, NO_x, CO, and HC, as well as generating particulates in the exhaust [1]. Modern engine research is focused towards less fuel consumption, less exhaust emissions, and higher engine efficiency [2, 3]. Modern spark-ignition (SI) engines generally use a three-way catalyst (TWC) along with a particulate filter to convert the emissions [4], and many advanced technologies such as downsizing, supercharging, and higher compression ratio (CR) have been introduced to improve engine efficiency; however, all these technologies are restricted by knock phenomena in achieving higher efficiency [5, 6]. Therefore, the study of knocking combustion must be adequately understood to meet the future demands of advanced engines. Figure 1 explicitly shows the autoignition occurrence inside the cylinder of SI engine which further responsible for conventional knock.

Figure 1. Autoignition occurrence inside the cylinder of SI engine

Knocking combustion is an uncontrolled combustion in the end gas in the cylinder. When the unburned charge of fuel and air mixture ahead of main flame front is exposed to high temperature for too long, the charge auto-ignites spontaneously resulting in an abrupt increase in temperature and pressure inside the cylinder [1]. It leads to a very sharp pressure gradient between the already burned mixture (by the main flame) and the auto-ignited mixture, and this steep pressure gradient is the start of a pressure wave with significant amplitude travelling through the burned gas with the local speed of sound [7]. When knock happens all the remaining heat is released extremely quickly, resulting in overheating and damage [4]. In knocking combustion, it is extremely essential to deduce the methodologies which characterize and detect knock [8-11], suppress knock [12-14], and the formation of knock [15, 16]. In order to avoid heavy damage and to achieve better performance during knocking combustion, it is also essential to precisely detect knock at the right movement. There have been many studies done that focused on knock predictions and detection techniques [17-19]. Knocking combustion can be distinguished by direct and indirect detection methods [20]. In-cylinder pressure analysis is the most promising direct detection method to determine the knock combustion, whereas knock can be identified indirectly by the combustion noise and vibrational signals [21]. When auto-ignition occurs, the pressure inside the chamber oscillates strongly, and an installed pressure sensor can detect the oscillation response, and a high pass band filter can then be used to differentiate the knocking combustion versus normal combustion; therefore this analysis is highly accurate

in monitoring knock [5, 6, 21]. However, this method is limited by transducer reliability and cost [22]. Additionally, the noise sensing method uses a noise frequency spectrum of the combustion, and analyzes the power of knock by estimating the sound pressure level in a specific frequency range [23]. There are many methods that can help to evaluate the frequencies induced during knocking processes, including the Fast Fourier Transform (FFT), Hilbert-Hung Transform (HHT), and wavelet analysis etc. [5, 7, 24-26].

Many studies have been done to investigate the factors that are responsible for instigating knock. Those influential factors are fuel property [27, 28], thermal boundary temperature [29], engine speed [30] compression ratio [31, 32], and number of spark plugs and their timing [5, 6, 33], etc. Among these factors, compression ratio (CR) is one of the most important parameters. The CR is directly related to the pressure inside the cylinder, and by increasing the CR, the pressure can be increased resulting in higher power output, reduced fuel consumption, and increased thermal efficiency of the engine [27]. However, an increase in CR leads to an escalation in the initial temperature and pressure of the mixture, an increase in flame propagation rate, a reduction in ignition delay period, and ultimately the knock propensity gets enhanced [31, 32, 34]. Therefore, knocking combustion is a major barrier to further increasing the CR of the engine and improving the efficiency of the engine. Additionally, several studies have been done to understand the effect of multiple spark plugs on engine performance. Davis et al. [35] used multiple spark plugs to reduce the cold start problem in engine, while researchers have also applied multiple ignition sites to eliminate the cycle-to-cycle variations in lean limit studies [36, 37] along with minimizing the fuel consumption and emissions [38, 39]. Pasternak et al. [40] Observed the effect of multiple spark ignition sites on knock occurrence, and reported that knock was more accessible by using multiple plugs compare to a single plug. Chen et al. [41] Used the synchronous double spark system to investigate their influence on engine performance and knock events, and deduced that a double spark arrangement was more liable to knock due to two propagating flames. They also reported that knock intensity could be reduced if the spark location was chosen near to the position where autoignition could occur. In our previous studies [5, 6, 33], we have triggered multiple spark plug strategies at lower CR to distinguished the knock mechanism, and perceived

that knock propensity and intensity increased by firing double and triple spark plugs, but that operation with four spark plugs could suppress the knock occurrence.

We have observed in our previous studies that multiple ignition sites have a strong effect on knock formation at low CR, and using five pressure sensors at various locations could help to detect the autoignition sites. But there is still a need to understand the effects of higher CR on knock initiation, power output, and other combustion characteristics by triggering multiple spark approaches, because higher CR leads to higher pressure and temperature inside the chamber which can provoke the violent knock. This work was an extension of our research, and the significance of this study was to facilitate the influence of three different CR (8.5, 9.5 and 10.5) on engine power output and knock mechanism by firing multiple spark plug strategies, and for that we installed four side spark plugs in a special liner extension at four radially equispaced distinct locations to propagate flames from those locations, provoking a distinct flame propagation from each and thus producing individual autoignition profiles. In addition, we have mounted six pressure sensors at distinct locations to precisely capture the pressure oscillation and acoustic wave propagations induced by knocking combustion inside the cylinder. The experiments were performed at naturally aspirated conditions, using the same fuel (91 RON gasoline) and fuel injection timing (SOI = -330 crank angle degrees (CAD) after top dead center (aTDC) and all at the stoichiometric air-fuel ratio. The maximum amplitude of pressure oscillation (MAPO) method was applied to determine the knock intensity, and the frequencies of the acoustic vibration modes produced by knock were calculated by FFT and wavelet analyses.

2. Experimental setup

2.1. Engine specification

The experiments were performed on a single-cylinder optical engine (AVL-5402). The base engine is a compression-ignition (CI) engine but it was converted to spark-ignition (SI) operation because it was expected to operate with higher knocking pressures than is normal for an SI engine. A port fuel injection

(PFI) system was installed in the inlet manifold, using a Bosch fuel injector (part number 62354). Figure 2 (a) represents the engine setup, and its detailed specifications are presented in Table 1. The inlet and exhaust valve timings are illustrated in Table 1, and valve lift of 0.25 mm was taken to define the valve timing. Figure 2 (b) shows the newly-designed metal liner fitted with its four spark plugs and four pressure transducers installed on the circumference of the metal liner. The spark plugs and pressure transducers were labelled from 1 to 4, to distinguish their firing number and measurement locations. The inner and outer diameters of the metal liner extension were 85 mm and 135 mm respectively, with a height of 29 mm. The engine was operated with a flat piston with 83.5 mm diameter, and adjustable plates were used to change the CR from 8.5, 9.5 and 10.5. The combustion chamber was a disc with edge ignition sites. The AVL PUMA open automation system was used to control the engine. In addition, Figure 2 (c) clearly shows the locations of four spark plugs along with all six pressure transducers, and their positions can be seen with respect to the inlet and exhaust valves. The spark plug (1) and plug (3) were located near the inlet and exhaust valves respectively while plug (2) and plug (4) were installed in between the valves. In knocking combustion, it is desirable to determine the autoignition location, pressure oscillations and combustion characteristics at various positions inside the chamber. To facilitate this, six pressure sensors were installed at different locations, four of them mounted on the circumference of the liner, one fitted at the center of cylinder head, and another one (the so-called “top sensor”) placed 35 mm offset from the center of cylinder head [5]. Moreover, the side spark plugs were fitted with a radial offset of 15° to the side pressure transducers, and the spark tips were over the flat piston to produce flames inside the cylinder [5]. The specifications of the spark plugs and pressure sensors are given in Table 2 and Table 3 respectively [5].

Table 1. Specifications of engine

Description	Specification
Type	Single-cylinder research engine
Stroke	90 mm
Bore	85 mm
Swept volume	511 cc
Piston geometry	Flat
Valve type	DOHC
Number of valves	Intake (2), Exhaust (2)
Intake valve	Open 10° CA bTDC
	Close 50° CA aBDC
Exhaust valve	Open 60° bBDC
	Close 0° aTDC

Table 2. Specifications of the pressure sensors used [5]

Description	Specification	
Type	GU22CK, AVL	GH15DK, AVL
Measuring range	0 - 350 bar	0 - 300 bar
Overload	400 bar	350 bar
Sensitivity	34 PC/bar	19 PC/bar
Linearity	$\leq \pm 0.3 \%$ FSO	$\leq \pm 0.3 \%$ FSO
Operating temperature range	-40 - 400 °C	-40 - 400 °C
Thermal sensitivity change	$\leq 1\%$, 20 - 400 °C, 0 - 300 bar	$\leq 2\%$, 20 - 400 °C, 0 - 300 bar
	$\leq \pm 0.25\%$, 250 $\pm$ 100 °C, 0 - 300 bar	$\leq \pm 0.5\%$, 250 $\pm$ 100 °C, 0 - 300 bar
Thermal shock error Δp (short-term drift)	$\leq \pm 0.3$ bar	$\leq \pm 0.4$ bar
Installed location	Top	Sides and center

Table 3. Specifications of the spark plugs used [5]

Description	Specification
Type	ER8EH, NGK
Spanner Size	13 mm
Outer thread	8 mm
Thread Length 1	12.7 mm
Thread Length 2	6.3 mm
Spark Position	1.3 mm
Interference suppression	5 kOhm

(a) Engine setup

(b) Special liner with 4 spark plugs and 4 pressure sensors (view from top)

(c) Positioning of spark plugs and pressure sensors

Figure 2. Schematic of Engine setup [5]

2.2. Operating conditions

The results were obtained at naturally aspirated conditions with the same fuel injection timing (SOI = -330 CAD aTDC) throughout and at stoichiometric air-fuel ratio (AFR) (i.e., $\lambda = 1$). An air heater and pressure regulator systems were used to keep inlet air temperature to approximately 25 °C and inlet pressure at 1 bar. The AVL Puma system was used to fix the oil and water temperatures at 90 °C. The pressure data was recorded by all the pressure sensors at an increment of 0.1 CAD. The AFR of the mixture was adjusted using a UEGO lambda sensor along with an electronic control unit. The speed of the engine was fixed at 1200 rpm, and an AVL data acquisition system was used [5]. 200 continuous firing cycles were recorded for 8.5 CR, while in the case of 9.5 and 10.5, less than 100 cycles were recorded during three and four spark plug operation at ST = -5 CAD aTDC, as a precaution due to heavy knock generation in these cases. In Table 4 can be seen all of the details of the operating parameters.

Table 4. Operating parameters

Engine speed	1200 rpm
Intake pressure (absolute)	1 bar
Intake temperature	25 °C
Coolant temperature	90 °C
Oil temperature	90 °C
Fuel injection pressure	6 bar
Fuel injection timing	-330 CAD aTDC
Fuel injection duration	6800 μ s
Relative air/fuel ratio (λ)	1

2.3. Fueling systems

The amount of fuel injection, timing and duration were controlled by IAV FI2RE software. The fuel injection pressure and duration were fixed at 6 bar and 6800 μ s to achieve $\lambda = 1$. An IndiCom module (IndiCom 2.4, AVL) was used to detect injector current signals [5]. In addition, the fuel temperature was stabilized by an AVL Fuel Temperature Controller (AVL-753C, AVL), and fuel flow rate was governed by an AVL fuel mass flow meter (AVL-735S, AVL) [1]. Haltermann CARB LEV III E10 gasoline fuel was used to perform the experiments; detailed fuel properties are listed in Table 5.

Table 5. Fuel properties (Haltermann CARB LEV III E10 Certification Gasoline) [5]

Research octane	91.0	Aromatics (% v/v)	22.5
Motor octane number	83.4	Olefins (% v/v)	5.7
Specific Gravity (SG)	0.7483	Ethanol (% v/v)	10.0
Lower heating value	41.9	H/C ratio	1.982
Energy density (MJ/L)	31.4	O/C ratio	0.0336

2.4. Spark plug Ignition approach

This study presents the effects of spark plug numbers and their location on knock initiation. Figure 3 shows the top view of four various locations of spark plugs installed on the liner along with their triggering approach, i.e. it shows the active spark plugs used for each test case. The intake valves are close to spark plug (1) while the exhaust valves are mounted near spark plug (3). The combustion process could be instigated by firing the spark plugs with various spark timings, locations, and active spark plug numbers under SI conditions. The pressure fluctuations encountered by firing these side spark plugs were investigated with help of the pressure sensors near to these spark plugs, which can potentially assist in locating the autoignition sites.

(a) Spark plug (1)

(b) Spark plug (1+3)

(c) Spark plug (1+2+3)

(d) Spark plug (1+2+3+4)

Figure 3. Schematic of the different spark plug locations and how the flame travels from them when they are active [5]

Note: A single cycle with maximum knock intensity was chosen to analyze the results given below.

3. Results and discussions

3.1. Pressure and heat release analysis

In-cylinder pressure is one of the most essential parameters of the combustion process [6]. A high band pass filter (> 4 kHz) was applied to process the recorded pressure data, estimate knock intensity, and observe frequencies in a specific range [5, 6]. In order to differentiate between normal and knocking combustion, the pressure trace and filter pressure graphs are shown in Figure 4 by firing spark plug (1) at CR 10.5, with the data recorded by the top sensor due to its higher sensitivity. Figure 4 (b) shows the pressure curve and pressure oscillation trend for a single specific knocking cycle, and a dotted blue vertical line is drawn to determine the first knock peak (pressure oscillation > 0.05 bar [5, 33]) which appeared at 9.7 CAD aTDC.

a) Normal Combustion at ST = -10 CAD aTDC

(b) Knocking Combustion at ST = -15 CAD aTDC

Figure 4. In-cylinder pressure and pressure oscillation by sparking plug 1 [at CR = 10.5]

Figure 5 shows the pressure trace and HRR graphs for the three CRs of 8.5, 9.5, and 10.5 (at fixed spark timing for these CRs) along with the effects of various sparking approaches, with data recorded by the top sensor due to its higher sensitivity. Figure 5 (a) was obtained by triggering the single spark plug (1) at ST = -15 CAD aTDC, which illustrates that by increasing the CR from 8.5 to 10.5, the pressure and HRR rise dramatically because of the higher pressure and temperature inside the cylinder which instigated autoignition earlier. The pressure and HRR traces were smooth for CR 8.5 which happened because knock was very weak at this state due to low pressure generation, but for the same operating conditions, the knocking behavior changed to moderate to strong knock as the CR increased to 9.5 and 10.5. However, Figure 5 (b) exhibits that by firing spark plug (1+3) knocking combustion was more intense for higher CR of 9.5 and 10.5 even at delayed spark timing (ST = -7 CAD aTDC) because it generated flames from two kernels which increased the pressure and temperature inside the chamber that helped to autoignite the unburned charge, but for the lower CR of 8.5 the knock was weaker. To investigate the effect of CR with more initiation sites, the triple spark plug (1+2+3) and quadruple spark plug (1+2+3+4) cases were triggered at the same spark timing of -5 CAD aTDC and the pressure and HRR data were recorded. ST = -5 CAD aTDC was chosen here because the earlier ST gave very strong knock for the higher CR, and to protect the engine it was recommended not to go for an earlier ST. Figure 5 (c) and (d) represent the effects of triggering

three and four spark plugs together on knock for the three different CRs. It can be explicitly seen that firing spark plug (1+2+3) has produced a stronger amplitude of pressure oscillation at a lower CR of 8.5 than spark plug (1+2+3+4) for the same operating conditions (although the pressure rise was higher with plug (1+2+3+4) but with a very smooth graph with fewer fluctuations). This is because at low CR the pressure was lower inside the chamber and plug (1+2+3+4) shows autoignition suppression effects due to faster composite flame propagation from four kernels. Since low octane number gasoline fuel was used, the end gas was easier to autoignite with the increased CRs of 9.5 and 10.5 due to higher pressures and temperatures inside the chamber; as a consequence the four spark plug (1+2+3+4) case encountered more vigorous knock than the three plug case (1+2+3) because the temperature was even higher during the combustion event.

(a) Spark plug (1), at ST = -15 CAD aTDC

(b) Spark plug (1+3), at ST = -7 CAD aTDC

(c) Spark plug (1+2+3), at ST = -5 CAD aTDC

(d) Spark plug (1+2+3+4), at ST = -5 CAD aTDC

Figure 5. Pressure and HRR traces for various spark plug approaches and different CRs

3.2. Combustion characteristics

The combustion phasing parameter CA50 represents the crank angle position at which 50 % of heat has been released by combustion. Figure 6 shows the effects of spark timing and compression ratio when using various spark approaches; this data was recorded by the top sensor. It can be seen that early ST brings forward CA50 values continuously, and higher CR leads to higher HRR which decreases the CA50 value for the same ST. Figure 6 (a) illustrates the variation by sparking plug (1), and for CR of 8.5 the range of ST was (-10 to -20 CAD aTDC), because beyond this range it was either weak combustion (after -10 CAD aTDC) or a strong knock case (earlier than -20 CAD aTDC). As the CR is increased to 9.5 to 10.5 the combustion was more stable for late ST but at the same time it gave stronger knock for an earlier ST. However, CR: 10.5 has given most advanced CA50 values for the same ST due to its faster burning rate, followed by CR: 9.5 and CR: 8.5. Values of CA50 less than 20 CAD aTDC were experienced at ST= -13 CAD aTDC for CR 10.5, while CR 9.5 and 8.5 showed CA50 values less than 20 CAD aTDC at ST = -17 CAD aTDC. Figure 6 (b) exhibits the effect of CR on CA50 by introducing two spark plugs (1+3), and it can be deduced that two plugs make the combustion more stable for late ST (such as 0 CAD) and CA50 less than 20 CAD aTDC could be easily achieved for late ST. Figure 6 (c) and (d) follow the same trend,

and as the number of active spark plugs increased, the combustion became more stable for later ST (e.g. 0 CAD aTDC), but knock was more violent for earlier ST. Four spark plugs (1+2+3+4) showed the most advanced CA50 values compared to all other cases for the same ST due to its faster global burning rate. For both the four plugs (1+2+3+4) and three plugs (1+2+3) cases, CA50 less than 20 CAD was obtained easily at a late ST of -5 CAD aTDC.

(a) Spark plug (1)

(b) Spark plug (1+3)

(c) Spark plug (1+2+3)

(d) Spark plug (1+2+3+4)

Figure 6. CA50 variation with respect to ST for various spark plug approaches and different CRs

The CR directly affects the power generated by an engine. Figure 7 presents the importance of the number of spark plugs and CR on net indicated mean effective pressure (IMEP). By sparking plug (1) at the same ST, the IMEP increased from 7.27 bar to 7.87 bar as the CR increased from 8.5 to 10.5 bar. However, two spark plugs (1+3) also followed the same trend and encountered the maximum IMEP value of around 8.1 bar for CR 10.5 at the same ST of -7 CAD aTDC. In addition, at ST = -5 CAD aTDC four spark plugs (1+2+3+4) gave more IMEP than three plugs (1+2+3) due to the fast global burning rate of charge inside the cylinder, the IMEP increasing from 7.88 bar to 8.46 bar as the CR changed from 8.5 to 10.5.

Figure 7. IMEP variation for various spark plug approaches and different CRs

Furthermore, the data can be used to determine the effects of multiple spark plugs and different CRs on ignition delay (ID) time, being defined as the time (in degrees) between ignition and beginning of combustion, itself considered to be 10% mass fraction burned. Figure 8 shows the effects of CR on ID variations by the various sparking stages. It can be seen that by increasing CR from 8.5 to 10.5, the ID reduced significantly for strategies, because higher CR produced higher pressure and temperature inside the cylinder. Using spark plug (1), the ID decreased from 23.75 to 16 CAD as the CR increased from 8.5 to 10.5 at the same ST of -15 CAD aTDC. Spark plug (1+3) a similar reduction in ID of 18 to 9 CAD for CR 8.5 to 10.5, even at the delayed ST of -7 CAD aTDC, because two flames are now propagating from the

spark plugs. The ID time produced by firing spark plugs (1+2+3) and (1+2+3+4) were compared at the same ST of -5 CAD aTDC; it was found that spark plug (1+2+3+4) produces an ID of 7.2 CAD at CR 10.5, because of its faster global flame propagation generated by four flame kernels.

Figure 8. Ignition delay variation for various spark plug approaches and different CRs

3.3. MAPO quantification

Figure 9 shows the schematic of the knock analyzer parameter maximum amplitude of pressure oscillation (MAPO), obtained from the knocking pressure signal recorded by a pressure transducer [10].

Figure 9. MAPO knock analyzer

Based on the filtered pressure data extracted from the pressure trace, the MAPO can be described in equation 1, as [5, 33].

$$\text{MAPO} = \max |P_{bf}| \quad (1)$$

Where P_{bf} is the high band pass filtered pressure in a window of -20 to 40 CAD aTDC, obtained in the frequency window of 4 - 25 kHz [4, 5]. The pressure signal experiences peak-to-peak fluctuations when autoignition occurs, and some pre-peaks appear before the maximum amplitude peak followed by some post-peaks. Figure 10 illustrates the peak-to-peak variation of amplitude of pressure oscillation instigated by autoignition which continues for several CAD before an instantaneous pressure rise appeared. A signal tool box in Matlab was applied to investigate the amplitude, position, and width of the local peaks [33]. In addition, a horizontal red line with the amplitude of pressure oscillation of 0.05 bar has been drawn in order to differentiate the normal combustion from knocking combustion peaks. Numbering has been applied above the peaks to show the pre-peaks and post-peaks around the maximum oscillation peak.

Figure 10. Peaks of filtered pressure signals by firing spark plug (1) at ST = -15 CAD aTDC and CR 10.5 (measured by the top sensor).

3.3.1. Peak-to peak-variation of pressure oscillation

Figure 11 demonstrates the effects of CR and numbers of spark plugs on the amplitude of pressure oscillation for some pre-peaks (marked -1 to -5), some post-peaks (marked 1 to 5) and the maximum amplitude peak (marked 0); the data was measured by the top sensor. It is perceivable from all the graphs

below that a higher CR leads to a higher MAPO value for all spark ignition site approaches. In most of the cases pre-peaks and post-peaks are also show the increasing amplitude trend as CRs increases. Figure 11 (a) and (c) only show three pre-peaks (-1 to -3) for the lower CR of 8.5 due to the lower pressure inside the chamber which instigates weaker oscillations initially. Figure 11 (b) illustrates the response by firing plug (1+3) at ST = -7 CAD aTDC. Here 8.5 CR causes a lower amplitude of pressure oscillations peaks due to weak knock, but as CR increases to 9.5 and 10.5 the pressure oscillations trends were more similar with higher magnitudes due to vigorous knock. In addition, the three spark plug (1+2+3) and four spark plug (1+2+3+4) conditions were triggered at the same ST of -5 CAD aTDC and the peak-to-peaks response of oscillation magnitude analyzed. It can be seen in Figure 11 (c) and (d) that the four plug case (1+2+3+4) shows a stronger MAPO value for higher CRs of 9.5 and 10.5 due to higher pressure and temperature inside the chamber.

(a) Spark plug (1), at ST = -15 CAD aTDC

(b) Spark plug (1+3), at ST = -7 CAD aTDC

(c) Spark plug (1+2+3), at ST = -5 CAD aTDC

(d) Spark plug (1+2+3+4), at ST = -5 CAD aTDC

Figure 11. MAPO peaks for various spark plug approaches and different CRs

3.3.2. Effect of ST on MAPO

ST has a crucial effect on knocking combustion, and is a controllable parameter that can determine the knock intensity [5]. Figure 12 shows the variation of MAPO with respect to ST for three different CRs along with various spark strategies; again, the data was monitored by the top sensor. All the graphs show that earlier ST instigated higher MAPO values for all CRs and spark strategies. It can also be observed for distinct spark approaches that as the CR increased, the MAPO value also increased due to higher pressure and temperature inside the chamber which provoking more intense knock. Figure 12 (a) illustrates that up to ST = -7 CAD aTDC, the single spark plug (1) case produces normal combustion for all the given CRs. However, the first knocking response was recorded at ST = -10 CAD aTDC for CR 9.5 and 10.5 (MAPO around 0.1 and 0.35 bar), while CR 8.5 has shown a first knocking combustion condition at ST = -13 CAD aTDC (MAPO of 0.08 bar). Moreover, plug (1+3) shows higher MAPO values even at delayed ST and it is not recommended to go to earlier ST for higher CRs; the results can be seen in Figure 12 (b). Figure 12 (c) and (d) show the three plug (1+2+3) and four plug (1+2+3+4) results with ST, and it can be perceived that the four plug case (1+2+3+4) produces lower MAPO values for the lower CR 8.5 due to fast flame propagation from four spark kernels which burn the charge faster and so reduce the time and volume

available for unburned charge to autoignite. However, sparking four plugs (1+2+3+4) instigated stronger MAPO values than three plugs (1+2+3) at the higher CRs of 9.5 and 10.5 because the pressure and temperature induced inside the chamber by firing four plugs were high enough to autoignite the fuel more easily than three spark plugs. Additionally, Table 6 summaries the detailed outcomes from Fig 6 and 12, which describes the effects of ignition timing and number of spark plugs on CA50 and knock intensity to determine the maximum brake torque (MBT) timing of the engine.

(a) Spark plug (1)

(b) Spark plug (1+3)

(c) Spark plug (1+2+3)

(d) Spark plug (1+2+3+4)

Figure 12. Effect of ST on MAPO for various spark plug approaches and different CRs

Table 6. Effects of spark plug numbers and ignition timing on combustion characteristics

Spark plug number	ST (CAD aTDC)	CR 8.5		CR 9.5		CR 10.5	
		CA50 (CAD aTDC)	MAPO (bar)	CA50 (CAD aTDC)	MAPO (bar)	CA50 (CAD aTDC)	MAPO (bar)
Spark plug (1)	-5	---	---	---	---	48	0.06
	-7	---	---	30.5	0.054	28	0.068
	-10	27.5	0.062	22.75	0.1	20.25	0.35
	-13	23.5	0.0714	21	0.33	18	1.054
	-15	22	0.439	20.75	1.43	16	2.34
	-17	19.25	3.4	18	5.45	---	---
	-20	11.5	5.2	---	---	---	---
Spark plug (1+3)	0	33	0.055	30	0.056	28.5	0.076
	-3	29.5	0.059	28.25	0.095	25	0.12
	-5	25.25	0.189	24.25	0.25	21.5	0.75
	-7	22.75	0.45	20	2.56	18.25	4.26
	-10	15.5	1.6	14	4.4	13	7
	-13	13.5	4.7	---	---	---	---
Spark plug (1+2+3)	0	28.5	0.071	26.5	0.18	25	0.26
	-3	22.5	0.13	21.5	0.6	19	0.75
	-5	19.75	0.51	18.5	0.85	17.25	1.2
	-7	17.5	1.23	---	---	---	---
	-10	12.75	5.1	---	---	---	---
Spark plug (1+2+3+4)	0	24	0.06	23	0.4	22.25	0.6
	-3	20.5	0.1	19.25	1.0	17.25	3.2
	-5	18.5	0.46	17.5	1.23	16.5	3.67
	-7	14.5	1.0	---	---	---	---
	-10	12	2.57	---	---	---	---

3.3.3. Cycle-to-cycle variation of MAPO

Knock is an abnormal phenomenon, with cycle-to-cycle variations during combustion [42]. Figure 13 illustrates the effects of CR and multiple spark approaches on MAPO values for 100 combustion cycles measured by the top pressure sensor. It can be seen from all the three graphs that sparking plug (1) and plugs (1+3) produced lower MAPO values, because of weak knock generation at particular spark timings (except for CR 8.5 where plugs (1+3) show a maximum MAPO of around 1 bar). However, Figure 13 (a) shows that at the same ST of -10 CAD aTDC, sparking three plugs (1+2+3) produced higher MAPO values (a maximum of 5.16 bar, and a mean of 0.97 bar) than four plugs (1+2+3+4) (2.57 bar and 0.81 bar, respectively) at the lower CR of 8.5 due to lower pressure generation inside the cylinder and four plug (1+2+3+4) has given suppression effect. However, by increasing the CR to 9.5 and 10.5, four plug operation (1+2+3+4) provoked a higher MAPO response than three plugs (1+2+3) at the same ST= -3 CAD aTDC, because the higher CR stimulated higher pressure and temperature inside the chamber which autoignites

the unburned charge more quickly with four spark plugs; these results are shown in Figure 13 (b) and (c). At CR 9.5, the maximum and mean MAPO values were 1.01 and 0.33 bar for four spark plugs (1+2+3+4), while three plugs (1+2+3) recorded maximum and mean MAPO values of 0.68 and 0.11 bar. Finally, at CR 10.5 the maximum and mean MAPO values were 3.2 and 0.88 bar for four spark plugs (1+2+3+4), while three plugs (1+2+3) produced values of 0.75 and 0.12 bar respectively.

(a) CR: 8.5

(b) CR: 9.5

(c) CR: 10.5

Figure 13. Cycle-to-cycle variation of MAPO for various spark plug approaches and different CRs

3.4 Determination of knock onset

This study also presents the significance of using multiple pressure transducers mounted at various locations to detect autoignition sites precisely. Figure 14 shows the influence of three different CRs on the first autoignition peak appearance with respect to crank angle degree recorded by the six pressure sensors along with their amplitude of pressure oscillation, by sparking plug (1+2+3+4) at $ST = -5$ CAD aTDC. It can be seen clearly from the graphs that CR has a strong effect on autoignition position with respect to CAD, because as the CR increases the crank angle position of the first knock peak decreases. Figure 14 (a) illustrates the response at CR 8.5 which shows the first autoignition peak has been detected by the side 2 sensor around 19.5 CAD aTDC followed by the top and side 4 sensors around 19.8 and 19.9 CAD aTDC. This implies the autoignition occurs near the side 2 sensor and initially the acoustic wave travels across the side 2 and side 4 because both are symmetrically located (top sensor is near side 4). However, as CR was increased from 8.5 to 9.5, autoignition occurred earlier than CR 8.5 for all the sensors and the first peak was reported at 13.5 CAD aTDC by side 3 sensor in the results shown in Figure 14 (b). Furthermore, CR 10.5 shows the earliest response from all six transducers, with the first peak appearing around 9.2 CAD aTDC for the side 3 sensor followed by the center and top sensors at 11 and 11.1 CAD aTDC. The variations in the crank angle values recorded by the various sensors reflect that there could be more than one autoignition sites inside the chamber (due to the higher CR) which traverse across the chamber and hit the sensors.

(a) CR = 8.5

(b) CR = 9.5

(c) CR = 10.5

Figure 14. First knock onset peak for various sensor locations and different CRs by sparking four plugs (1+2+3+4) at ST = -5 CAD aTDC

Figure 15 represents the impact of CR on MAPO position with respect to CAD for the same knocking cycle as above. The results follow the same trend, and for the higher CR the autoignition initiated earlier because it has increased the temperature and pressure inside the cylinder which forces the unburned charge towards autoignition more quickly. We can clearly observe from Figure 15 (c) that 10.5 CR

generated MAPO earlier for all the sensors due to vigorous knock, followed by CR 9.5. However, CR 8.5 has produced delayed MAPO location with respect to crank angle because of weak knock instigation, and the result can be seen in Figure 15 (a).

Figure 15. MAPO Knock onset peak for various sensor locations and different CRs by sparking four plug (1+2+3+4) at ST = -5 CAD aTDC

3.5 Frequency analysis

3.5.1 Acoustic resonance mode

When autoignition occurs, a high rate of heat release is seen, which excites the various vibration modes inside the chamber [43, 44]. These vibration modes produce pressure waves which traverse the cylinder at the local speed of sound [4-7]. These vibration modes can be circumferential, axial or radial as discussed by Draper [7]. The axial mode can be neglected due to the smaller height above the piston with respect to the cylinder bore [4, 5]. The knock frequencies for various vibration modes by considering cylinder bore and perimeter as characteristic parameters can be evaluated by the equation given below [4, 5].

$$f_{m,n} = \frac{C \cdot \rho_{m,n}}{\pi \cdot B} \quad (2)$$

Where

$f_{m,n}$ = specific vibration frequency for mode m, n [Hz]

C = local sound of speed [m/s]

$\rho_{m,n}$ = resonance mode factor

B = cylinder bore diameter [m]

m = circumferential mode number

n = radial oscillation mode number

The theoretical frequencies associated with various acoustics modes by sparking four plugs (1+2+3+4) at ST = -5 CAD aTDC, and using equation 2 are illustrated in Table 7. The numerous vibration modes report various forms of pressure wave with the determining modes.

Table 7. Acoustic resonance modes of a cylindrical combustion chamber [5, 7]

(m, n)	(1, 0)	(0, 1)	(1, 1)	(2, 0)	(3, 0)	(4, 0)
Mode shape
$\rho_{m,n}$	1.841	3.832	5.332	3.054	4.201	5.318
f_{theory} (kHz)	7.831	16.299	22.679	12.989	17.868	22.619

3.5.2 Fast Fourier transform (FFT)

FFT analysis was applied to investigate the effects of CR (by firing multiple spark plugs) on frequencies in the space domain in knocking combustion. During knocking combustion, when the main flame front collides with autoignition, an acoustic wave is generated which travels across the chamber with various resonance modes so it is essential to detect those vibration modes to deduce the range of frequencies present in the signal [4, 5]. Figure 16 represents the FFT results of the three CRs by sparking four plugs (1+2+3+4) at ST = -5 CAD aTDC, with the responses recorded by all six pressure sensors mounted at distinct locations to identify the various vibration modes produced by knock. When four spark plugs (1+2+3+4) were triggered the flames started propagating from all the four kernels toward the center, and the most likely area left for end gas to autoignite was the center space of the chamber; because of that it produced various circumferential and radial acoustic modes inside the cylinder. Figure 16 shows that higher CRs lead to higher amplitude of frequencies, with the maximum amplitudes created by the 10.5 CR due to stronger knock while CR 8.5 shows minimum amplitudes due to weaker knock. Figure 16 (a) demonstrates the frequency range measured by the top sensor, with the clear peak of (1, 0) circumferential harmonic mode within a frequency range of 6 to 8 kHz for CR 10.5 and 9.5 but for CR 8.5 the response is not as obvious. The significance of using the center sensor was to detect the radial vibration mode of (0, 1) in a frequency domain of 15 to 17 kHz, and it can be seen in Figure 16 (b) that all the CRs have displayed this mode. In addition, Figure 16 (c) to (f) monitor the FFT analysis recorded by all the side sensors at various locations. It can be seen from the graphs that all the side sensors have revealed the dominant resonance mode of (1,

0) with frequencies monitored between 6 to 8 kHz for all three CRs (but their amplitudes are different). Besides, higher CR 10.5 has also shown some other lower peaks of circumferential acoustic modes of (2, 0) and (3, 0) with frequency bands of 10 to 13 kHz and 17 to 18 kHz, which means a higher CR provokes other acoustic oscillation modes due to intense knock.

(a) Top sensor

(b) Center sensor

(c) Side 1 sensor

(d) Side 2 sensor

(e) Side 3 sensor

(f) Side 4 sensor

Figure 16. FFT analysis for various sensor locations and different CRs by sparking four plugs (1+2+3+4) at ST = -5 CAD aTDC

Note: The y-axis scale is similar for all the graphs above except Figure 16 (b), because to show the obvious response it has been scale down.

3.5.3 Wavelet transform

Wavelet analysis is a significant tool to determine the frequency variation with respect to the time domain [5]. Figure 17 illustrates the 3-D wavelet spectrum obtained by firing four plugs (1+2+3+4) at ST = -5 CAD aTDC for the three distinct CRs, and the response was recorded by the highly sensitive top sensor. The range of frequencies with respect to crank angle along with their power (magnitude) can be observed in the figures. Moreover, the discrete frequency bands were focused between 10 to 30 CAD aTDC for the current operating conditions for all the three CRs, and it is also noticeable in the figures below that the power of the spectra gets elevated as the CRs increased. However, the power of the various frequency bands reduces slightly during the main combustion duration, attributed to attenuation of in-cylinder vibration [5]. Figure 17 (a) reflects the results for CR 8.5 that shows the main frequency bands of 6 – 8 kHz, 11 – 13 kHz and 15 – 17 kHz, which demonstrate the (1, 0), (2, 0) and (0, 1) resonance modes respectively, and the overall power spectra are weak due to weak knock. In addition, as CR was increased from 8.5 to 9.5 the power spectra increased as shown in Figure 17 (b), because the higher pressure rise provoked moderate knock.

The dominant circumferential mode of (1, 0) displayed the highest power along with some other low power modes of (2, 0) and (3, 0) with frequency bands 11 – 13 kHz and 17 – 19 kHz. Similarly, Figure 17 (c) presents the response obtained at CR 10.5, with the maximum power spectra due to the intense knock triggered by it. The primary mode of (1, 0) has the maximum power while the other modes of (0, 1) and (3, 0) show a lower power spectrum. Note the acoustic mode (0, 1) represents the radial vibration mode which generally originates from autoignition located in the center of the chamber, with the resulting knocking oscillations mainly transmitted from the center to the circumference which then bounce back from different directions as a result of the wave/wall interaction.

(a) CR = 8.5

(b) CR = 9.5

(c) CR = 10.5

Figure 17. Wavelet analysis for different CRs by sparking four plugs (1+2+3+4) at ST = -5 CAD aTDC

4. Conclusion

This paper presented a new approach to investigating flame propagation by using various spark plug strategies, along with the effect of varying CR on knock formation. This paper also describes the significance of multiple ignition sites along with CR on engine power output (IMEP), and combustion durations, which has not been covered in previous studies. Different end gas zones were generated by triggering distinct spark stages to observe the knock characteristics along with autoignition locations. Additionally, six pressure sensors were installed at different locations to precisely determine the knock vibrational signal receiving from those different directions. In summary, the knocking combustion research discussed in this paper has revealed the following:

1. Adding more side spark plugs together with increasing CR can increase the in-cylinder pressure and HRR. As the CR increased from 8.5 to 10.5, the multiple ignition sites have resulted in a significant rise in pressure and HRR together with earlier knock onset.

2. At the same ST, sparking four plugs (1+2+3+4) has shown lower pressure oscillation than three plugs (1+2+3) at the lower CR of 8.5 because the flames generated by the four kernels suppressed the propensity for the unburned charge to autoignite. But since low octane fuels are not suitable for higher CR (9.5 and 10.5) operation, as a consequence, four spark plugs triggered higher pressure oscillations and HRR than three plugs for the same operating conditions.
3. Compared to all the spark strategies, firing plug (1+2+3+4) produced a maximum IMEP value of 8.46 bar along with lowest ignition delay of 7.2 CAD aTDC at a CR of 10.5, due to higher pressure and temperature inside the chamber.
4. This study also facilitates the effects of ST and CR on knock propensity and MAPO. It was observed that earlier ST enhanced the knock tendency and MAPO values with an increasing number of spark plugs and CR. From cycle-to-cycle variations, it can be seen that at the lower CR of 8.5, triple spark plug (1+2+3) operation generated higher MAPO values than four spark plugs. But as CR increased to 9.5 and 10.5, four spark plugs (1+2+3+4) produced stronger MAPO values due to higher pressure and temperature inside the cylinder helping to autoignite the unburned charge.
5. Multiple pressure sensors were used to detect the autoignition sites precisely, and it was determined that knock onsets were generated earlier by increasing the CR 8.5 to 10.5. This means higher CR instigates knock onset earlier due to a rise in pressure and temperature inside the cylinder.
6. Sparking four plugs (1+2+3+4) generated various vibrational frequency modes for three different CRs at the same ST, and the response was measured by all the pressure sensors located at various locations. However, all the sides sensors along with the top sensor recorded the clear peak of (1, 0) circumferential vibrational mode with a frequency range of 6 – 8 kHz, and the center sensor showed the (0, 1) radial mode for all three CRs albeit with different magnitudes. It was also observed that higher CR leads to some other harmonic modes of (2, 0) and (3, 0) with frequency bands of 10 to 13 kHz and 17 to 18 kHz respectively due to intense knock.

7. Wavelet analysis determined the frequency spectra based on crank angle positions present in the pressure signal, and the results have illustrated the various acoustic vibrational modes with different power ranges based on CR. The lower CR 8.5 has shown a low power spectrum due to weak knock, while CR 10.5 has triggered higher power spectra for various harmonic modes due to violent knock induced by sparking four plugs (1+2+3+4) at the same ST.

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Definitions/Abbreviations

aTDC	After top dead center
bTDC	Before top dead center
BDC	Bottom dead center
CAD	Crank angle degree
CI	Compression ignition
CR	Compression ratio
ECU	Electronic control unit
FFT	Fast Fourier transform
HC	Hydrocarbon
HRR	Heat release rate
IC	Internal combustion
IMEP	Indicated mean effective pressure
MAPO	Maximum amplitude of pressure oscillation
MON	Motor octane number
P_f	Filtered pressure
PFI	Port fuel injection
RON	Research octane number
SI	Spark ignition
SOI	Start of injection
ST	Spark timing
TWC	Three way catalyst
UHC	Unburned hydrocarbon

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