THE INFLUENCE OF VALVE TIMING ON IN-CYLINDER PRESSURE SPARK IGNITION ENGINES PERFORMANCE CHARACTERISTICS

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Article history
Received
26th May 2023
Revised
30th October 2023
Accepted
16th November 2023
Published
1st December 2023

ABSTRACT

The performance of the engine depends on many factors. One of the factors is valve timing known to be the timing of opening and closing of valves that has a significant effect on the in-cylinder performance. However, there is less information in the study about valve timing effect on single cylinder engine performances. In this study, the focus is to analyze in-cylinder pressure characteristics on a single piston fuel injection for a spark-ignition engine. This can be done by simulating the effects of valve timing on in-cylinder pressure. The methodology of this project will be simulation-based by using commercial one-dimensional software. The research results are engine performance parameters which are volumetric efficiency, brake torque, brake power, and cylinder pressure in 1000 to 5500 RPM engines. The results show a positive increment in engine performance from the baseline model (CTA240) which is 9.06% for brake power, 2.85% for brake torque, and 13.09% for volumetric efficiency. At low engine speed, it was also found improvement in cylinder pressure when advancing the intake valve timing opening (IVO) by 20 to 25 degrees. For high speed, the cylinder pressure was found to improve once the retardation of intake valve timing closing (IVC) was done between 40 to 45 degrees by comparing it with the baseline results. The result highlights the importance of intake valve timing setup by varying the opening and closing of the intake valve to give better output for engine performance.

Keywords: *Valve timing, In-cylinder pressure, Engine performance*

1.0 INTRODUCTION

The performance of an internal combustion engine is intricately linked to the mass flow rates of both air and fuel that are introduced into the engine's cylinders. Enhancing the mass flow rate of air contributes to the augmentation of the engine's intake capacity, commonly referred to as its volumetric efficiency. This significant parameter substantially governs the resultant torque and power outputs generated by the engine [1]-[4]. Notably, the application of devices like superchargers and turbochargers has been explored to elevate volumetric efficiency. As the mass flow rate of air increases, due to enhanced volumetric efficiency facilitated by mechanisms such as superchargers or turbochargers, a greater volume of air is available within the cylinder during the intake stroke. This augmented air volume leads to an increased air-fuel mixture density, promoting

DOI: https://doi.org/10.11113/jm.v46.493

more efficient combustion. The subsequent rise in in-cylinder pressure is directly correlated with enhanced combustion efficiency, resulting in elevated torque and power outputs [5], [6].

In internal combustion engines, especially for spark ignition (SI) engines, valve events and their timings have had a significant impact on overall engine performance. Varying the engine parameters such as valve timing is a promising alternative to enhance the overall engine performance. Several previous studies stated engine systems that adapted variable valve timing systems had advantages on engine performances [1], [7], [9]. The variable valve timing system controls the timing of the intake valve opening (IVO) and intake valve closing (IVC) during the intake process, and the valve profile are significant contributor to improving volumetric and thermal efficiency and achieving improved engine performance [11].

For a relatively long time, the proper management of the intake and exhaust valve timing has been seen as an efficient way to boost engine torque delivery [10]. In addition, this paper by [12] states that a proper choice of valve timing will lead to substantial reductions in pumping losses during a component load operation. Then, the versatility of the valve timing, length, lift or combination of these may theoretically result in an improvement in the efficiency, fuel economy, and emissions of SI engines [13]. Dergisi [14] explained that controlling valve activities and timings allows the maximum possible loading of the cylinder at all engine speeds. Moreover, the other studies also state that the experimental studies demonstrate that the timing of the intake valve closure is a major factor that influences engine output and emissions [15]. When both valve and spark timings are optimized, the ideal timing for each valve appears to exhibit a linear dependence on the engine load [8]. Kakaee et. al [16] also states that variable valve timing is one of the most reliable approaches that not only decreases fuel consumption and engine emissions but also addresses low-end torque issues.

There are several numbers of parameters that affect the performance of the engine. So, these parameters must be deeply analyzed as it is important in order to maximize engine performance. One of the important parameters is valve timing. This parameter has been considered as a factor in the development of a more advanced SI engine for maximizing performance. Different timing valves will produce different in-cylinder pressure characteristics [12]. The researchers use various methods which are simulation and experimental for this study setup. According to Pauras [11] the simulation software used is Ricardo Wave for the study of valve timing. However, less information has been given to investigate the relationship between valve timing to in- cylinder pressure of fuel injection of a spark-ignition engine [12], [17], [18], [11]. As a result, the lack of thorough study makes it difficult to study the effect of valve timing in detail. The researchers also did the research mostly on multi-cylinder engines compared to a single cylinder [19], [16], [20] but in this study, the research is limited to a single cylinder engine.

The effect of valve timing needs to be identified and properly analyzed to investigate the correlation of valve timing to in-cylinder pressure characteristics. The study will be done using a simulation method in order to identify the effect of valve timing on the in-cylinder pressure of the spark-ignition engine.

2.0 METHODOLOGY

2.1 Simulation Model

In this study, the one-dimensional software is used to investigate the in-cylinder pressure, volumetric efficiency, brake torque and brake power. The engine specifications are from the Maruicci [21] such as bore, connecting rod length, compression ratio, maximum lift for both intake and exhaust valve and period of valve opening are listed in Table 1.

Valve timing variation is limited to 0 to 10 degrees advanced from TDC for intake valve opening and 50 to 60 degrees after BDC for intake valve closing. The reason is due to the typical IVO timing is about 0 to 10 degrees before the TDC, which results in a reasonably symmetrical overlap of the valve around the TDC [12]. Next, Asmus [23] states that further delay in the IVO causes the cylinder pressure to dip momentarily below the intake manifold pressure. It also states that the timing of IVC is the single most important determinant of the equilibrium of low-speed and high-speed volumetric efficiency. The amount of fresh charge trapped in the cylinder is largely dictated by IVC and this will significantly affect engine performance and economy.

Table 1: Single Cylinder Engine Specification [21]

Engine Parameters	Specification
Bore	89.0 cm
Stroke	79.5 cm
Rod Length	13.81 cm
Compression Ratio	10.5:1
Maximum Valve Lift	
Intake	0.914 cm
Exhaust	0.937 cm
Valve Timing	
Intake Open	308.0 CAD
Intake Duration	286.0 CAD
Exhaust Open	86.5 CAD
Exhaust Duration	326.0 CAD

The crank angle degree (CAD) represents the timing of the engine crankshaft and directly drives the camshaft which manages the intake and exhaust valve timing and lifting. The cam timing of opening and closing valves is determined by valve lift profile trends [18]. Cam timing angle (CTA) is used to control the location of maximum valve lift. The cam-timing angle is the angle between the Cam Timing Anchor Reference and the Cam Timing Lift Array Reference. In this case, TDCFiring was chosen as the Cam Timing Anchor Reference. Next, Theta=0 indicates that the Cam Timing Angle above will be referenced to the 0.0 value in the Angle Array. Figure 1 shows the exhaust valve lift profile.

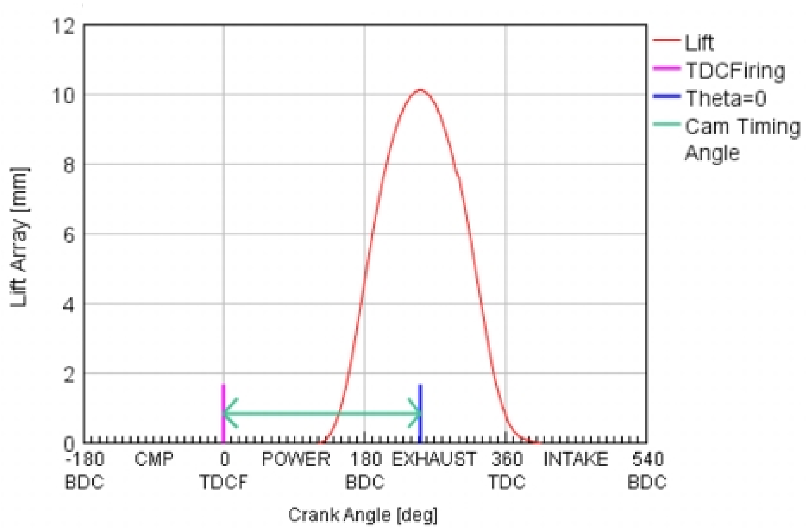

Figure 1: Valve lift configuration

Table 2 shows the variation in intake valve timing. The intake cam timing angle (CTA) or duration of valve timing can be calculated by adding 180° to the intake valve closing and opening.

Table 2: Intake valve timing configuration

	Intake Valve Opening (IVO) at bTDC	Intake Valve Closing (IVC) at aBDC	Intake Cam Timing Angle (CTA) duration
Advance of Intake Valve Opening	25 °	20 °	225 °
	20 °	20 °	220 °
	15 °	20 °	215 °
	10 °	20 °	210 °
Retard of Intake Valve Closing	10 °	40 °	230 °
	10 °	45 °	235 °
	10 °	55 °	245 °
	10 °	60 °	250 °

2.2 Mathematical calculation and formula

The ensuing mathematical expressions are utilized to quantitatively determine a range of crucial engine performance indicators. These encompass significant factors such as volumetric efficiency, brake torque and brake power.

Volumetric efficiency, η_v can be defined as the ratio between the quantity of air introduced into the engine cylinder, $\dot{m}_{actual}$ and the quantity of air that would be able to enter under optimal standard atmospheric conditions, $\dot{m}_{theory}$ that can be calculated by using equation (1).

$$\eta_v = \frac{\dot{m}_{actual}}{\dot{m}_{theory}} x100\% \tag{1}$$

Brake power, P_b is an indicator of engine performance that requires brake torque, T information. The brake torque is typically obtained from the engine dynamometer testing. The brake power calculation is expressed by equation (2).

$$P_b = \frac{2\pi NT}{60} \tag{2}$$

2.3 Validation study

A validation study is conducted compared to the Mariucci [21]. The parameter compared is volumetric efficiency values from the simulation compared with volumetric efficiency from experimental data Maruicci [21]. The relative error gathered from the simulation software is tabulated in Table 3.

Table 3: Relative error for volumetric efficiency values between Maruicci [21] and the baseline model (CTA240).

Engine speed (RPM)	Volumetric efficiency by Maruicci [11] (%)	Volumetric efficiency (%) by baseline model (CTA240)	Relative error (%)
1000	87.0	83.2	4.37
1500	93.0	90.7	2.47
2000	85.0	83.8	0.94
2500	92.0	94.1	1.74
3000	103.5	112.0	8.21
3500	101.0	92.0	8.91
4000	100.0	102.0	2.00
4500	98.5	102.0	3.55
5000	95.0	101.0	6.32
5500	81.0	84.4	4.20

DOI: https://doi.org/10.11113/jm.v46.493

In a nutshell, the relative error is accepted as it is lower than 10% [24],]25]. The engine model proved to be more accurate and near to accurate experimental results.

3.0 RESULTS AND DISCUSSION

3.1 Volumetric efficiency

Volumetric efficiency is a measurement of the effectiveness of engine breathing which depends on the amount of incoming charge that travels through the intake system. It is determined by dividing the actual mass flow rate of air consumed by the theoretical air mass flow rate that is drawn based on displacement volume. The resulting variations in volumetric efficiency are shown in Figure 2. The graph showed a significantly declined trendline from low speed to high speed of the simulated engine model. The volumetric efficiency was seen to increase dramatically to the peak as the engine speed was at a low speed (1500 RPM). The increment started from 210 degrees until 235 degrees of cam timing angle above the baseline engine model which is 240 degrees. The volumetric efficiency for low cam timing angle was seen as most affected as it dropped drastically at the rpm 2000 compared to baseline cam timing angle and above. The volumetric efficiency with varied cam timing was seen to decline once it was inside the range of the high-speed engine (5500 RPM). The highest volumetric efficiency obtained is 156 % at 1000 RPM with a cam timing angle (210 degrees) compared to the baseline cam timing. The lowest volumetric efficiency achieved was about 61.4 % at 5500 RPM when the cam timing angle was 210 degrees. To further increase the volumetric efficiency of the engine, the valve timing variation was needed and properly setup to achieve it. From the results, it can be seen that different cam timing angle gives different result in terms of volumetric efficiency performance.

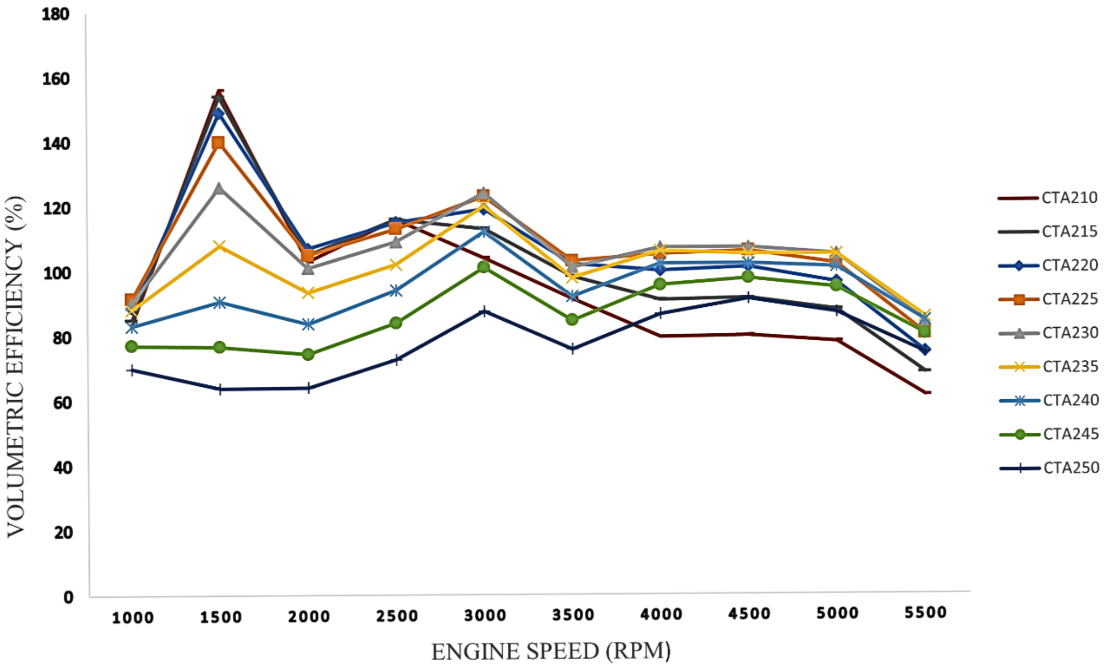

Figure 2: Volumetric efficiency with a variation of valve timing

DOI: https://doi.org/10.11113/jm.v46.493

3.2 Brake torque

The brake torque in Figure 3 was seen to increase dramatically to the peak as the engine speed was at 1500 RPM. It can be seen that the cam timing angle above the baseline engine model (CTA240) is affected by these results. However, the brake torque performances that varied with low cam timing angle were seen to decrease at the high speed between 3500 RPM to 5500 RPM. A low cam timing angle was seen to increase the brake torque performances at low speed whereas the opposite at the high-speed engine. The lowest brake torque obtained was about 17.9 Nm at 5500 RPM. Brake torque was rapidly decreased when the cam timing angle adjusted too far from the baseline timing.

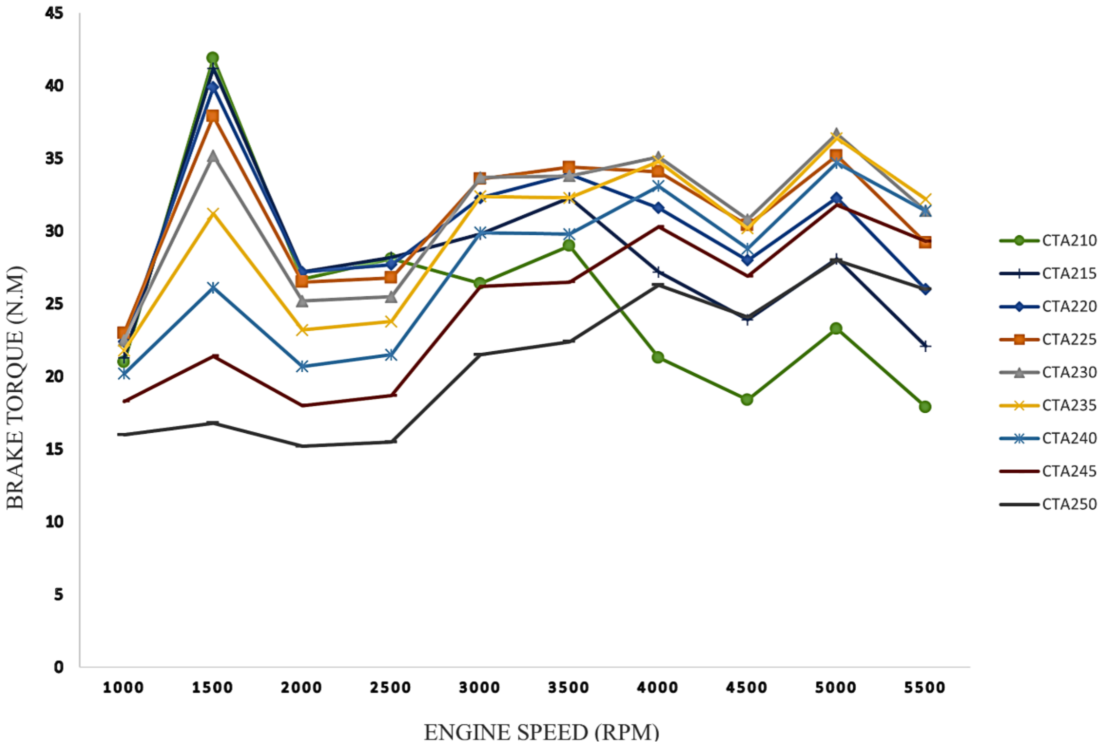

Figure 3: Brake torque with a variation of valve timing

3.3 Brake power

As shown in Figure 4 a steady increment of the trendline from low speed to high speed of the simulated engine model between (1000 to 5000 RPM). However, it shows some slight drop at high-speed engine (5500 RPM) for lower cam timing angle. It was also seen to decline below the baseline once it was at high-speed engine (5500 RPM), whereas the opposite was for a higher cam timing angle which is an increase above the baseline. The highest brake power achieved is about 19.2 kW at a high-speed engine with a cam timing angle (230 degrees). The lowest brake power was 2 kW at a low-speed engine for a cam timing angle (210 degrees). This shows that brake power is affected by varying the intake valve timing of the engine.

DOI: https://doi.org/10.11113/jm.v46.493

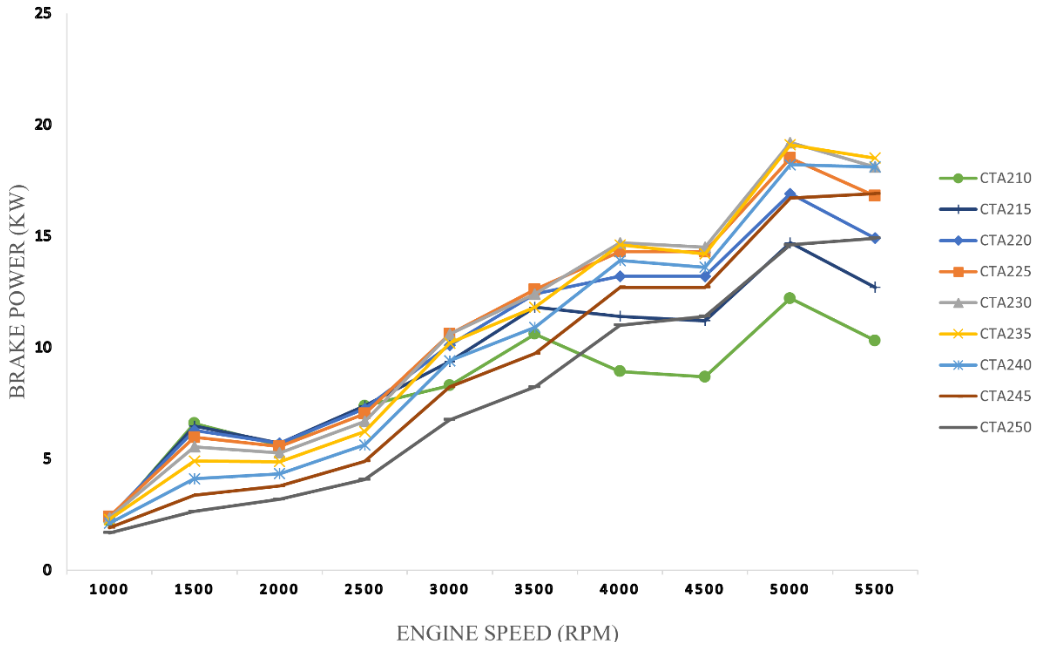

Figure 4: Brake power with a variation of valve timing

3.4 In-cylinder pressure

Figure 5 shows the cylinder pressure for different cam timing angles at a low-speed engine which is 1500 RPM. The increment of cylinder pressure for each valve timing event was observed. The highest in-cylinder pressure obtained is about 35.533 bar with a cam timing angle (210 degrees). The lowest in-cylinder pressure achieved was about 18.449 bar at a cam timing angle of 250 degrees. This shows that the cylinder pressure result for cam timing 210 degrees is higher than the baseline due to advancing the IVO about 10 degrees from TDC. Then, retarding the IVC too far will drop the cylinder pressure below the baseline. From the results, it can be seen that different valve timing events influence the in-cylinder pressure performance.

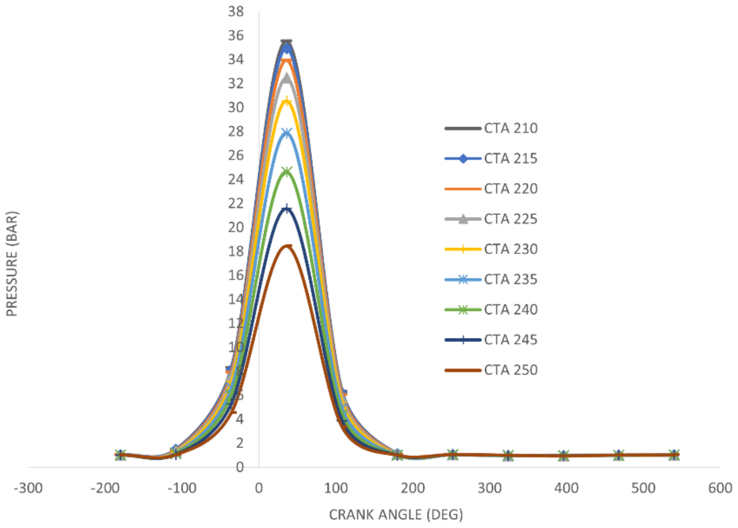

Figure 5: In-cylinder pressure at 1500 RPM

DOI: https://doi.org/10.11113/jm.v46.493

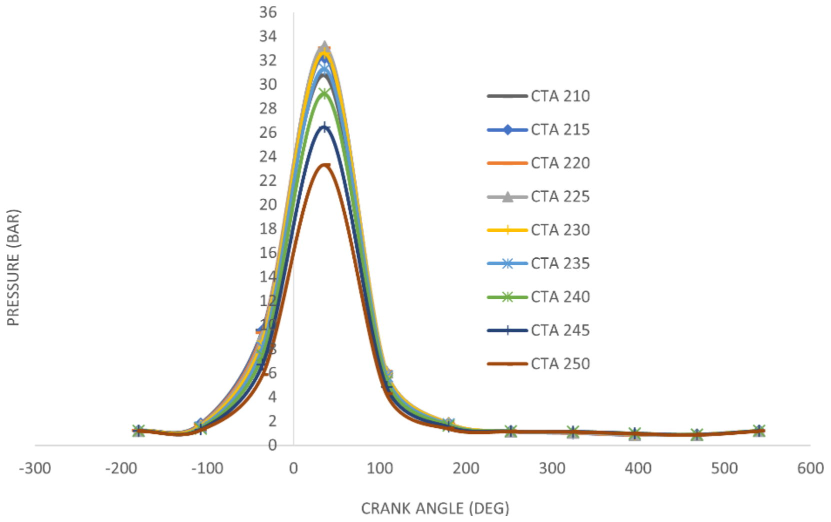

Figure 6: In-cylinder pressure at 3000 RPM

In Figure 6, the results of the cylinder pressure for different cam timing angles at 3000 RPM were shown. The increment of cylinder pressure for each valve timing event especially between the compression and power stage in the engine process was observed. This was identified around the area of TDCF. The highest in-cylinder pressure obtained is about 33.159 bar with a cam timing angle (225 degrees). The lowest in-cylinder pressure achieved was about 23.289 bar at a cam timing angle of 250 degrees. This shows that the cylinder pressure result for cam timing 225 degrees is higher than the baseline due to advancing the IVO about 25 degrees from TDC. Then, retarding the IVC too far will drop the cylinder pressure below the baseline. Advancing the IVO in the range of 10 to 25 degrees bTDC and retarding IVC below 45 degrees aBDC will increase the cylinder pressure, especially for low-speed engines.

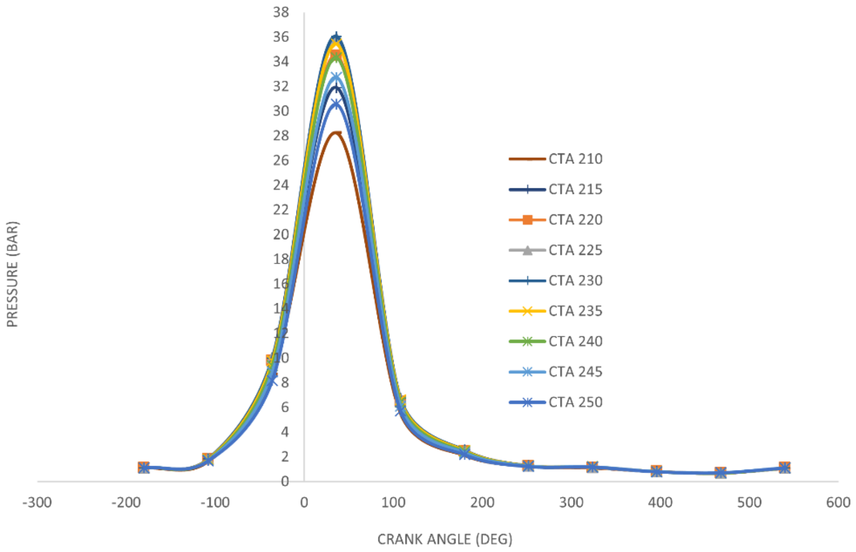

Figure 7: In-cylinder pressure at 4500 RPM

DOI: https://doi.org/10.11113/jm.v46.493

Figure 7 shows the cylinder pressure for different cam timing angles at a high-speed engine which is 4500 RPM. The cylinder pressure of the simulated engine was seen to increase dramatically as it entered an area between the compression and power stage which is around in crank angle of 0 degrees (TDCF). The highest in-cylinder pressure obtained is about 36.048 bar with a cam timing angle (230 degrees). The lowest in-cylinder pressure achieved was about 28.237 bar at a cam timing angle of 210 degrees. This shows that the cylinder pressure result for cam timing 230 degrees is higher than the baseline due to retarding the IVC about 40 degrees aBDC. Then, by advancing the IVO will drop the cylinder pressure below the baseline.

The CTA240 model refers to the baseline model engine performance parameters results which is when the cam timing angle is set to 240 degrees. These data are used for the comparison of the results between simulated data. This shows that different intake valve timing gives different results in terms of engine performance. Valve timing adjustment, duration, lift or any of these could result in the improvement of the engine performance of the spark ignition engines [13].

The volumetric efficiency shows some improvement when the cam timing angle is varied. This showed a noticeable increase in volumetric efficiency by advancing the IVO angle from 25 degrees to 10 degrees bTDC. It then experiences a reduction of volumetric efficiency which is about 0.79 % once the reduction of IVO angle occurs. From the result, the early IVO angle gives a better improvement in terms of volumetric efficiency compared to the late IVO angle bTDC. The highest improvement recorded was about 13.09 % as the IVO angle advanced for 25 degrees bTDC or 225 degrees of cam timing angle.

Then, the brake torque also shows some improvement which is 3.25 % from the baseline. This is done by advancing the intake valve opening about 25 degrees bTDC. However, the brake torque was seen to show some reduction of about 15.70 % once the IVO angle reduced to 10 degrees bTDC. The hypothesis that can be made is the retarding the IVO further gives a less brake torque improvement compared to the early IVO bTDC.

It also shows changes in brake power with the IVO. An improvement of about 7.76 % was obtained as the IVO was advanced by about 25 degrees bTDC. This was achieved by comparing baseline and varied IVO data. However, the brake power was seen to show some reduction of about 19.46 % from the baseline as the IVO reduces to 10 degrees angle bTDC or 210 degrees of cam timing angle. These results show that the timing of the IVO can significantly affect engine performance.

The volumetric efficiency shows some improvement once the cam timing angle is varied. This shows a noticeable decrease in volumetric efficiency by retarding the IVC angle from 40 degrees to 60 degrees aBDC. From the result, the early IVC angle gives a better improvement in terms of volumetric efficiency compared to the late IVC angle aBDC. The highest improvement recorded was about 11.56 % as the IVC angle is 40 degrees aBDC or 230 degrees of cam timing angle.

Then, the brake torque also shows some improvement which is 2.85 % from the baseline. This is done due to the late intake valve closing about 40 degrees aBDC. However, the brake torque was seen to show some reduction of about 29.70 % once the IVC angle retard further from BDC. The hypothesis that can be made is the retarding the IVC further gives a less brake torque improvement compared to the early IVC aBDC.

It also shows changes in brake power with the IVC. An improvement of about 9.06 % was obtained as the IVC was at 40 degrees aBDC. This was achieved by comparing baseline and varied IVO data. However, the brake power was seen to show some reduction of about 21.77 % from the baseline as the IVC retards further to 60 degrees angle aBDC or 250 degrees of cam timing angle. From these results, precise valve timing events are crucial to achieve better engine performance.

At the valve setting CTA210, the highest peak of volumetric efficiency, brake torque and brake power were predicted at 1500 RPM. The factor contributing to the peak depends on the right opening of the intake valve during the incoming positive pressure of air volume drawn into the engine cylinder. The positive pressure of air volume significantly increases the volumetric efficiency and subsequently improves the engine brake torque and brake power at 1500 RPM which impacts the overall fuel consumption. The right timing of incoming positive pressure of air varies with the engine speeds and limitation mechanical design of the valve management system and engine limits the maximum output that can be produced.

4.0 CONCLUSION

In conclusion, advancing the intake valve opening (IVO) about 25 degrees bTDC or 225 degrees of cam timing angle results in a greater positive impact on engine performance parameters at low engine speed. The results show that retarding the intake valve closing (IVC) at about 40 degrees aBDC or 230 degrees of cam timing angle can improve the efficiency in terms of engine performance parameters for high-speed engines. The highest cylinder pressure in a low-speed engine was obtained if the intake valve opening (IVO) is being advanced bTDC which is a cam timing angle between 220 to 225 degrees. While for high-speed engines, the highest in-cylinder pressure was obtained as the retardation of intake valve closing (IVO) was done between cam timing angles 230 to 235 degrees. The performance of cylinder pressure is crucial in order to generate more power for the engine. As the cylinder pressure increased, the net engine power was also increased. The higher cylinder pressure also was found in high-speed engines and lower cylinder pressure was declared in low-speed engines. The intake valve timing which is CTA230 degrees is selected as the best performance intake for this study as the net cylinder pressure (67.9 bar), volumetric efficiency (126 %), brake power (19.2 kW) and brake torque (36.7 Nm) were obtained and shows an improvement compared to baseline result. Despite the CTA210 giving the highest volumetric efficiency and brake torque at low speed, it also shows a reduction when entering a high-speed engine which is below the baseline results.

ACKNOWLEDGMENTS

The authors would like to express gratitude to everyone involved in this project. This research is funded by the Fundamental Research Grant Scheme (600-IRMI/FRGS 5/3(084/2019) from the Ministry of Education, and Universiti Teknologi MARA, Cawangan Pulau Pinang.

NOMENCLATURE

CTA	*Cam timing angle*
CAD	*Crank angle degree*
bTDC	*Before top depth center*
aBDC	*After bottom depth center*
IVO	*Intake valve opening*
IVC	*Intake valve closing*
TDC	Top depth center
BDC	Bottom depth center
TDCF	Top depth center firing
η_v	Volumetric efficiency, %
$\dot{m}_{actual}$	Actual ass flow rate, kg/s
$\dot{m}_{theory}$	Theoretical mass flow rate, kg/s
P_b	Brake power, W
T	Engine torque, N.m
N	Engine speed, RPM

DOI: https://doi.org/10.11113/jm.v46.493

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DOI: https://doi.org/10.11113/jm.v46.493